CHAPTER 6

EVALUATION OF PUSH-OUT TEST RESULTS

6.1 Introduction

As demonstrated in Chapter 4, the AISC equations give conservative predictions of the strengths of studs in solid slabs, but not in composite slabs. Therefore, it is necessary to modify or replace the AISC equations for the strength of studs when steel deck is used. An evaluation of a large number of push-out test results is performed in this chapter. This analysis forms the foundation for a new stud strength prediction method that is summarized at the end of this chapter.

All tests, except the tests described in Sections 3.4.3 – 3.4.5, performed at VT (including those by Sublett et al (1992), Lyons et al (1994), and Diaz et al (1998)) will be used in the development of the new strength prediction model. Tests by other researchers will also be used to verify the model.

Several researchers have shown that the position of the stud in the deck rib has significant impact on the strength of the stud (Mottram and Johnson (1990), Lloyd and Wright (1990), Sublett et al (1992), Lawson (1992), Easterling et al (1993), Lyons et al (1994), and Johnson and Yuan (1997)). Therefore, the tests performed at VT, for the purpose of the analysis herein, are separated into these categories:

- Strong position, single studs in 2 in. and 3 in. deck
- Weak position, single studs in 2 in. and 3 in. deck
- Middle position, single studs in 1 in. and 1 1/2 in. deck

- Staggered position studs in 2 in. deck
- Strong position, pairs of studs in 2 in. and 3 in. deck
- Middle position, pairs of studs in 1 in. deck

A breakdown of the VT test parameters and the number of tests in each category is given in Table 6.1.

Table 6.1 Number of Push-Out Tests Used in Analysis By Category

Stud Diameter	Deck Height	Stud Position						Total
		S	W	2S	Stag	M	2M	
3/8"	1"					6	3	*9*
	1.5"							*0*
	2"	3	3					*6*
	3"	3	3					*6*
1/2"	1"					6	3	*9*
	1.5"							*0*
	2"	6	6	6				*18*
	3"							*0*
5/8"	1"					12		*12*
	1.5"							*0*
	2"	6	6	5				*17*
	3"							*0*
3/4"	1"							*0*
	1.5"					2		*2*
	2"	28	17	23	21			*89*
	3"	17	8		9			*34*
	Total	*63*	*43*	*34*	*30*	*26*	*6*	*202*

Models will be developed for strong, weak, and middle position single studs. The strength of staggered studs and pairs of studs will then be investigated.

Only tests with a stud diameter to flange thickness ratio, *d/t*, less than or equal to 2.7, as recommended by Goble (1968), and 20 or 22 gauge deck will be used in the initial development of the model. The effect on stud strength of $d/t > 2.7$ will then be discussed, as will the effect of the deck thickness (gauge) for weak position studs.

Once the prediction model is developed based on the VT tests, test data from other researchers will be checked against the model. This other test data will include the use of other deck profiles, more than two studs per rib, and lightweight concrete.

6.2 Statistics Used in the Analysis of Data

When comparing the experimental values to the values predicted by a model, one must use statistics to determine if the prediction method is suitable. The most commonly used "number" to determine this suitability is the coefficient of correlation, or "R value". This coefficient "measures the degree to which the measured and predicted values agree and is used as a measure of the accuracy of future predictions" (Ayyub and McCuen 1997). The formula is given below, where x_i are predicted values from the model, and y_i are experimental values.

$$R = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{\sqrt{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2}\sqrt{\sum_{i=1}^{n} y_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right)}} \tag{6.1}$$

This value measures the linear relationship of two sets of values. The closer R is to zero, the less linear the relationship (called a "null correlation"); an R of 1.0 means the values are perfectly linear with each other. It is very important to note that the one thing that R

does not do is test whether the two sets of values are linearly related on a 1:1 ratio, which is necessary for the model to be accurate.

Once the experimental values are found to be highly dependent on a certain variable, meaning that R is close to 1.0, the slope of the linear relationship can be found by plotting the experimental values versus the variable, and drawing a "best-fit" line through the data points. For the analyses presented herein, this best-fit line was produced using the software Excel.

One can then calculate the ratios of the experimental values to the predicted values. The average of these ratios should be close to 1.0 if the steps in the previous paragraph are followed. One may then look at the minimum ratio (ideally close to 1.0), the maximum ratio (ideally close to 1.0), and the coefficient of variation (which is the standard of deviation divided by the mean, and is ideally close to zero).

Each prediction model developed was evaluated using the steps described above.

6.3 Single Studs in Composite Slabs

6.3.1 Strong Position Single Studs in 2 in. and 3 in. Deck

Tests on single strong position studs from Sublett et al (1992), Lyons et al (1994), and this study, with the exception of the tests discussed in Sections 3.4.3 – 3.4.5, were used in the development of a strength prediction model for single strong position studs. The tests that were used had $d/t \leq 2.7$ and 20 or 22 gauge deck. It is widely accepted that this difference in deck thickness does not influence stud strength for studs in the strong position. The influence of d/t will be discussed after an appropriate model has been developed. Only 2 in. and 3 in. composite deck and 10% normal load were used.

The experimental strength, Q_e, of a strong stud was taken as the maximum load reached during testing. The maximum loads, in 16 of the 21 tests conducted in this study on single strong position studs, occurred before 0.2 in. of slip was attained, as reported in Table 6.2. The average slip at maximum load for strong position studs was 0.14 in. In cases where the maximum load was reached after 0.2 in. of slip, the maximum load was very close to the load at 0.2 in. slip; i.e., the load-slip plot had already "leveled out" at 0.2 in. slip. It also appears that smaller diameter studs reach their maximum loads at smaller slips than larger diameter studs: 3/8 in. diameter studs reached maximum loads at an average slip of 0.07 in., 1/2 in. studs at 0.10 in., 5/8 in. studs at 0.20 in., and 3/4 in. studs at 0.23 in. These values are shown graphically in Fig. 6.1.

After plotting the experimental strengths, Q_e, against each of the test variables, it was apparent that the strongest influence on stud strength for strong position studs is the tensile strength of the stud, A_sF_u. A best-fit line, with a y-intercept of zero, was drawn through the data points in Fig. 6.2, giving a slope of 0.68. This yields the equation

$$Q_{1S} = 0.68 A_s F_u \tag{6.2}$$

to predict the strength of single strong position studs. These predicted strengths are compared to the experimental strengths in Table 6.3. The following statistics were calculated for Eqn. 6.2:

Table 6.2 Slip at Maximum Load and Loads at 0.2 in. Slip for Single Strong Position Studs

Program	Series	Test	Stud Dia. (in.)	Qe (k)	Slip at Q_e (in.)	$Q_{e\,0.2''}$** (k)
Rambo-Roddenberry	D16	D46	0.375	5.89	0.0643	*
Rambo-Roddenberry	D16	D47	0.375	5.18	0.0451	*
Rambo-Roddenberry	D16	D48	0.375	5.36	0.0917	*
Rambo-Roddenberry	D20	D58	0.375	6.03	0.0100	*
Rambo-Roddenberry	D20	D59	0.375	8.1	0.1317	5.22
Rambo-Roddenberry	D20	D60	0.375	9.5	0.0741	*
Rambo-Roddenberry	D7	D19	0.5	8.86	0.0829	*
Rambo-Roddenberry	D7	D20	0.5	9.14	0.0869	*
Rambo-Roddenberry	D7	D21	0.5	6.63	0.0690	*
Rambo-Roddenberry	D1	D1	0.5	9.77	0.1486	*
Rambo-Roddenberry	D1	D2	0.5	7.29	0.1161	6.74
Rambo-Roddenberry	D1	D3	0.5	9.23	0.1003	8.74
Rambo-Roddenberry	D4	D10	0.625	12.53	0.2144	12.37
Rambo-Roddenberry	D4	D11	0.625	13.54	0.2677	13.35
Rambo-Roddenberry	D4	D12	0.625	15.55	0.2757	15.38
Rambo-Roddenberry	D13	D37	0.625	16.18	0.1703	*
Rambo-Roddenberry	D13	D38	0.625	17.07	0.1792	*
Rambo-Roddenberry	D13	D39	0.625	14.53	0.1094	*
Rambo-Roddenberry	D10	D28	0.75	20.01	0.2515	19.87
Rambo-Roddenberry	D10	D29	0.75	18.72	0.1821	*
Rambo-Roddenberry	D10	D30	0.75	21.8	0.2578	21.57

* Blanks indicate that failure occurred before all slip readings reached 0.2 in.

** Loads were interpolated from test data

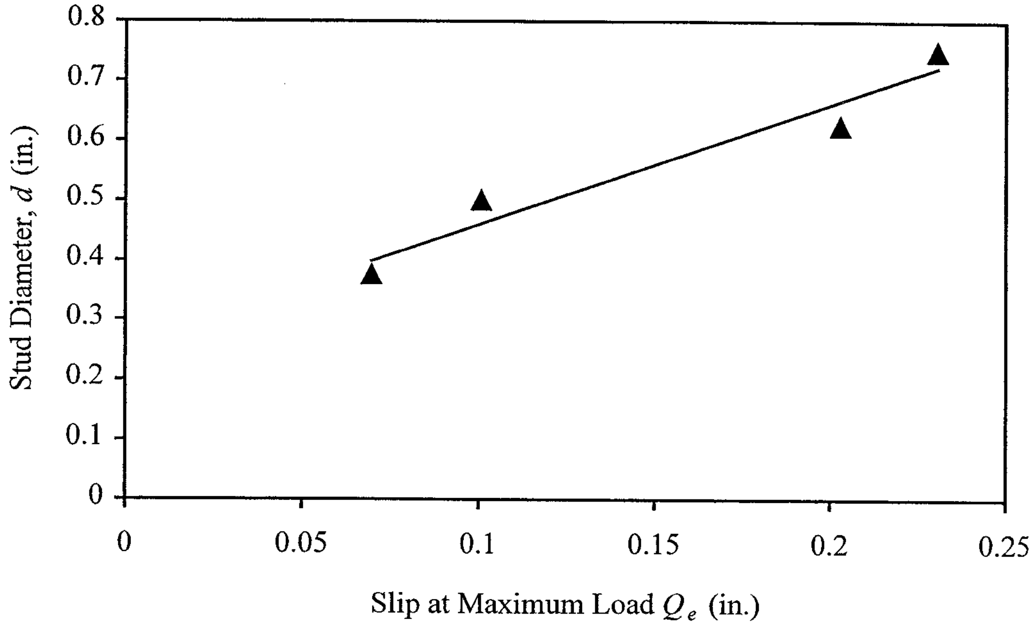

Fig. 6.1 Stud Diameter vs. Slip at Maximum Load for Single Strong Position Studs

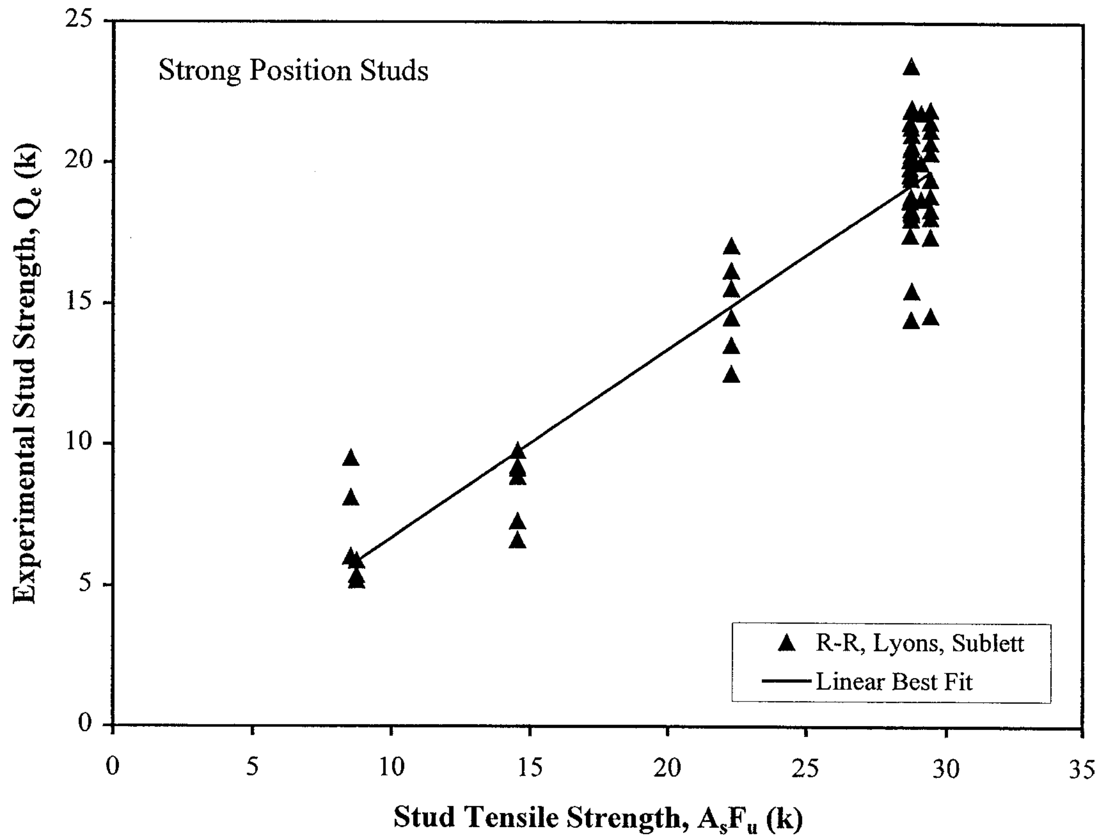

Fig. 6.2 Experimental Stud Strength vs. Stud Tensile Strength of Single Strong Position Studs

Table 6.3 Predicted Stud Strengths of Single Strong Position Studs

Program	Series	Test	$0.68A_sF_u$ (k)	Q_e (k)	$Q_e/0.68A_sF_u$
Rambo-Roddenberry	D1	D1	9.89	9.77	0.988
Rambo-Roddenberry	D1	D2	9.89	7.29	0.737
Rambo-Roddenberry	D1	D3	9.89	9.23	0.934
Rambo-Roddenberry	D4	D10	15.15	12.53	0.827
Rambo-Roddenberry	D4	D11	15.15	13.54	0.894
Rambo-Roddenberry	D4	D12	15.15	15.55	1.026
Rambo-Roddenberry	D7	D19	9.89	8.86	0.896
Rambo-Roddenberry	D7	D20	9.89	9.14	0.924
Rambo-Roddenberry	D7	D21	9.89	6.63	0.671
Rambo-Roddenberry	D10	D28	19.77	20.01	1.012
Rambo-Roddenberry	D10	D29	19.77	18.72	0.947
Rambo-Roddenberry	D10	D30	19.77	21.80	1.103
Rambo-Roddenberry	D13	D37	15.15	16.18	1.068
Rambo-Roddenberry	D13	D38	15.15	17.07	1.126
Rambo-Roddenberry	D13	D39	15.15	14.53	0.959
Rambo-Roddenberry	D16	D46	5.95	5.89	0.990
Rambo-Roddenberry	D16	D47	5.95	5.18	0.871
Rambo-Roddenberry	D16	D48	5.95	5.36	0.901
Rambo-Roddenberry	D20	D58	5.80	6.03	1.039
Rambo-Roddenberry	D20	D59	5.80	8.10	1.396
Rambo-Roddenberry	D20	D60	5.80	9.50	1.638
Lyons	1	D2	20.00	21.91	1.096
Lyons	1	D3	20.00	18.08	0.904
Lyons	2	D4	20.00	19.44	0.972
Lyons	2	D5	20.00	18.85	0.943
Lyons	2	D6	20.00	20.73	1.037
Lyons	3	D7	20.00	21.18	1.059
Lyons	3	D8	20.00	20.37	1.019
Lyons	3	D9	20.00	21.46	1.073
Lyons	4	D10	19.54	20.62	1.055
Lyons	4	D11	19.54	21.02	1.076
Lyons	4	D12	19.54	21.97	1.124
Lyons	5	D13	19.51	19.84	1.017
Lyons	5	D14	19.51	20.14	1.033
Lyons	5	D15	19.51	21.45	1.100
Lyons	6	D52	20.00	17.39	0.870
Lyons	6	D53	20.00	14.61	0.731
Lyons	6	D54	20.00	18.35	0.918
Lyons	7	D55	19.54	18.21	0.932
Lyons	7	D56	19.54	15.49	0.793
Lyons	7	D57	19.54	18.30	0.936
Lyons	8	D58	19.51	18.67	0.957
Lyons	8	D59	19.51	19.60	1.005
Lyons	8	D60	19.51	17.45	0.895
Sublett	1	1A	19.53	18.83	0.964
Sublett	1	1B	19.53	20.30	1.040
Sublett	3	3A	19.53	19.47	0.997
Sublett	3	3B	19.53	18.40	0.942
Sublett	8	8B	19.53	21.29	1.090
Sublett	13	13A	19.53	18.28	0.936
Sublett	13	13B	19.53	20.53	1.051
Sublett	14	14A	19.53	23.48	1.202
Sublett	14	14B	19.53	21.89	1.121
Sublett	15	15A	19.53	18.03	0.923
Sublett	15	15B	19.53	19.66	1.007
Sublett	17	17A	19.53	14.48	0.742
Sublett	17	17B	19.53	18.76	0.961

$R = 0.930$

Average ratio $Q_{e\,ave.}/0.68A_sF_u = 0.991$

Minimum ratio $Q_{e\,ave.}/0.68A_sF_u = 0.671$

Maximum ratio $Q_{e\,ave.}/0.68A_sF_u = 1.638$

Coefficient of variation = 15.0%

The scatter in the data in Fig. 6.2 is lessened and the coefficient of correlation is improved if the averages of the experimental stud strengths for each series are used. The worst correlation is for the 3/8 in. diameter studs in 3 in. deck, where the experimental strengths were underpredicted by Eqn. 6.2.

To investigate the effect of concrete strength on stud strength, the experimental strengths were divided by $0.68A_sF_u$ and plotted against the concrete strengths in Fig. 6.3. There appears to be no correlation between stud strength and concrete strength for single strong position studs tested at VT, for either 2 in. or 3 in. deck. This is also discussed in Section 6.6.1. It also appears that the stud strength is not dependent on the deck height, which is also discussed in Section 6.7.

Strong position studs usually fail either by stud shearing or concrete pull-out. One may argue that the strength of studs that fail by concrete pull-out should be dependent on the concrete strength. To investigate this matter, the data from Sublett et al (1992) was analyzed. Using $0.68A_sF_u$ from Eqn. 6.2 for the predicted strength of these tests, stud connections exhibiting concrete failures (i.e., concrete pull-out) had ratios of $Q_e/0.68A_sF_u$ close to 1.0 as desired, just as those studs having stud shearing failures. The

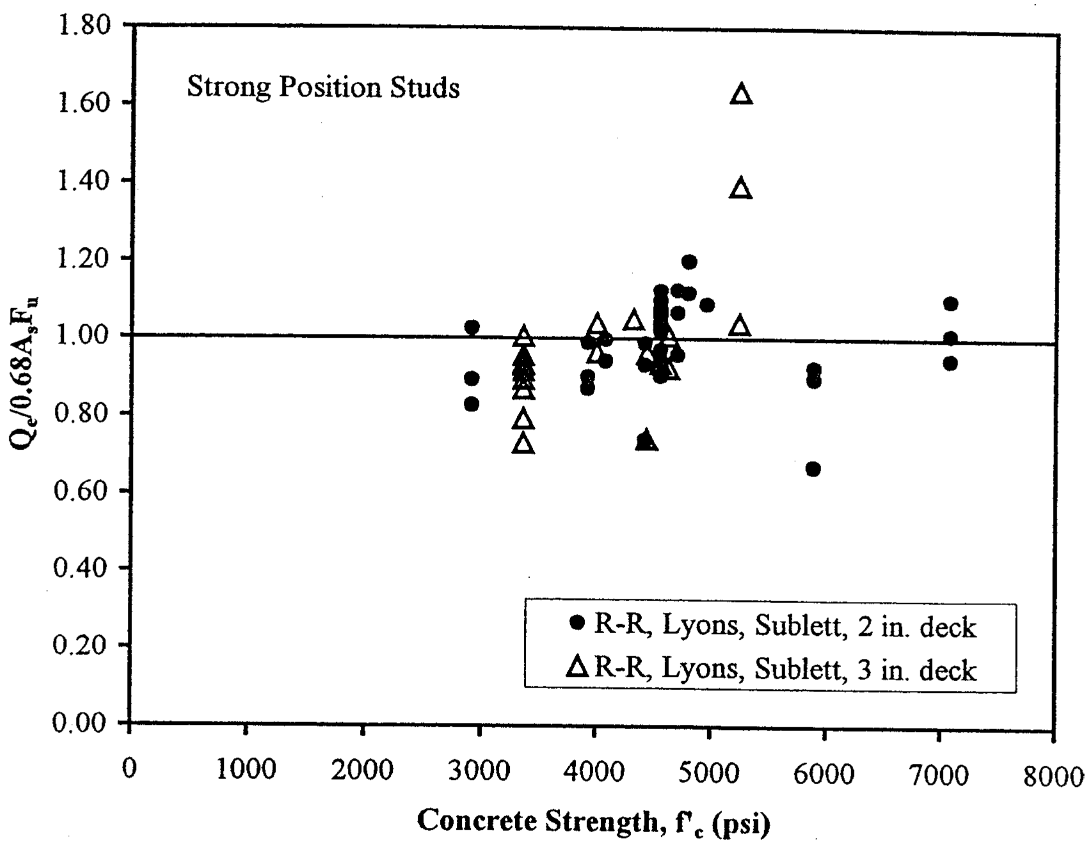

Fig. 6.3 Effect of Concrete Strength on Stud Strength of Single Strong Position Studs

strengths of studs with concrete failures were normalized to a concrete strength of 4000 psi using the following formula:

$$Q_{e\,norm} = Q_e\left(\frac{4000}{f_c^{'}}\right)^n \tag{6.3}$$

"Roots," or values of n, between 0 and 1.0 in the equation above were attempted, but did not result in higher R values. Nor was there a change in R when the strengths of the studs with all failures were normalized to a concrete strength of 4000 psi.

6.3.2 Weak Position Single Studs in 2 in. and 3 in. Deck

Tests on single weak position studs from Sublett et al (1992), Lyons et al (1994), and this study, with the exception of the tests discussed in Sections 3.4.3 – 3.4.5, were used in the development of a strength prediction model for single weak position studs. The tests that were used had $d/t \leq 2.7$ and either 2 in. or 3 in. deep 20 gauge composite deck. It was shown by Lyons et al (1994) from several push-out tests that the strength of a weak position stud is highly dependent on the deck strength. This effect will be discussed in Section 6.3.3. Also to be discussed, in Section 6.10, will be the influence of $d/t > 2.7$ on stud strength.

The load-slip plots for single weak position studs show that the first peak in the load occurs around 0.2 in. of slip. This occurs about the time that rib punching is observed. The load either drops or remains about the same thereafter for several increments of slip. When very large slips are reached, the studs begin to bear directly on the deck; this sometimes causes the load to increase. It was decided to use, as the "useful strength", the largest load that was reached before an average slip of 0.2 in. occurred. This strength is defined as "$Q_{e\,0.2''}$". It is interesting to note that the ratio of $Q_e/Q_{e\,0.2''}$ (the ratio of the maximum capacity to the useful capacity) in this study was 1.0 for 3/8 in. studs, increasing to 1.07 for 1/2 in. studs, to 1.15 for 5/8 in. studs, down to 1.12 for 3/4 in. studs. The trend is for larger diameter studs to have an increase in strength after 0.2 in. of slip or at larger slips. The smaller diameter studs usually failed in shear before they "pushed through" enough concrete to bear onto the deck, and therefore usually did not have an increase in capacity at large slips. Larger diameter studs seem to be more affected by the deck strength than smaller diameter studs.

After plotting $Q_{e\ 0.2''}$ against each of the test variables, it was apparent that the strongest influence on stud strength for weak position studs is the tensile strength of the stud, A_sF_u. A best-fit line, with a y-intercept of zero, was drawn through the data points in Fig. 6.4, giving a slope of 0.48. This yields the equation

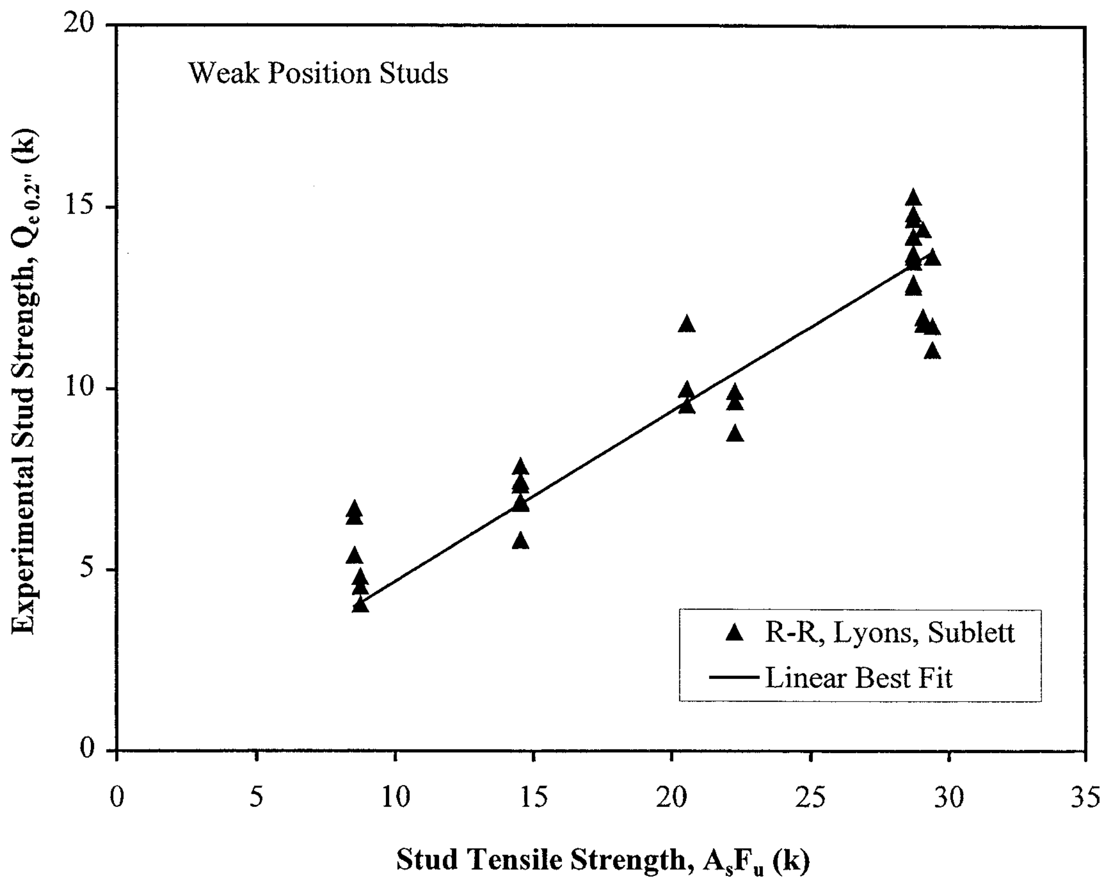

Fig. 6.4 Experimental Stud Strength at or Before 0.2" Slip vs. Stud Tensile Strength of Single Weak Position Studs

$$Q_{1W} = 0.48 A_s F_u \tag{6.4}$$

to predict the strength of single weak position studs. These predicted strengths are compared to the experimental strengths in Table 6.4. An even better fit was obtained

Table 6.4 Predicted Strengths of Single Weak Position Studs

Program	Series	Test	$0.48A_sF_u$ (k)	$Q_{e\,0.2''}$ (k)	$Q_{e\,0.2''}/0.48A_sF_u$	$Q_{e\,0.2''\,ave.}$ (k)	$Q_{e\,0.2''\,ave.}/0.48A_sF_u$
Rambo-Roddenberry	D3	D7	6.98	5.81	0.833	6.69	0.96
Rambo-Roddenberry	D3	D8	6.98	7.44	1.066		
Rambo-Roddenberry	D3	D9	6.98	6.82	0.977		
Rambo-Roddenberry	D5	D13	9.87	11.81	1.197	10.45	1.06
Rambo-Roddenberry	D5	D14	9.87	9.99	1.012		
Rambo-Roddenberry	D5	D15	9.87	9.55	0.968		
Rambo-Roddenberry	D9	D25	6.98	7.85	1.125	7.35	1.05
Rambo-Roddenberry	D9	D26	6.98	7.32	1.049		
Rambo-Roddenberry	D9	D27	6.98	6.88	0.986		
Rambo-Roddenberry	D12	D34	13.96	11.81	0.846	12.74	0.91
Rambo-Roddenberry	D12	D35	13.96	12.00	0.860		
Rambo-Roddenberry	D12	D36	13.96	14.42	1.033		
Rambo-Roddenberry	D15	D43	10.70	8.78	0.821	9.45	0.88
Rambo-Roddenberry	D15	D44	10.70	9.64	0.901		
Rambo-Roddenberry	D15	D45	10.70	9.93	0.928		
Rambo-Roddenberry	D18	D52	4.20	4.05	0.965	4.47	1.06
Rambo-Roddenberry	D18	D53	4.20	4.54	1.081		
Rambo-Roddenberry	D18	D54	4.20	4.81	1.146		
Rambo-Roddenberry	D22	D64	4.09	5.40	1.319	6.18	1.51
Rambo-Roddenberry	D22	D65	4.09	6.68	1.631		
Rambo-Roddenberry	D22	D66	4.09	6.46	1.578		
Lyons	21	D43	14.12	11.09	0.786	12.17	0.86
Lyons	21	D44	14.12	11.75	0.832		
Lyons	21	D45	14.12	13.66	0.968		
Sublett	2	2A	13.78	14.20	1.030	14.45	1.05
Sublett	2	2B	13.78	14.70	1.066		
Sublett	4	4A	13.78	13.52	0.981	13.64	0.99
Sublett	4	4B	13.78	13.75	0.998		
Sublett	12	12A	13.78	15.31	1.111	15.08	1.09
Sublett	12	12B	13.78	14.85	1.077		
Sublett	16	16A	13.78	13.66	0.991	13.25	0.96
Sublett	16	16B	13.78	12.84	0.932		
Sublett	18	18A	13.78	12.92	0.937	13.57	0.98
Sublett	18	18B	13.78	14.22	1.032		

with an exponential function, yielding the equation $Q_{1W} = 3.61e^{0.046A_sF_u}$ with a coefficient of correlation of 0.947. However, it is simpler to use the linear relationship. The following statistics were calculated for Eqn. 6.4:

R = 0.943

Average ratio $Q_{e\,0.2''}/0.48A_sF_u$ = 1.03

Minimum ratio $Q_{e\,0.2''}/0.48A_sF_u$ = 0.786

Maximum ratio $Q_{e\,0.2''}/0.48A_sF_u$ = 1.63

Coefficient of variation = 17.9%

The scatter in the data in Fig. 6.4 is lessened and the coefficient of correlation is improved if the averages of the experimental stud strengths for each series are used. The worst correlation was obtained for the three tests on 3/8 in. diameter weak position studs using 3 in. deck; the experimental strengths were underestimated by Eqn. 6.4.

To investigate the effect of concrete strength on stud strength, the experimental strengths were divided by $0.48A_sF_u$ and plotted against the concrete strengths in Fig. 6.5. There appears to be no correlation between stud strength and concrete strength for single weak position studs tested at VT for 2 in. deck. There does appear to be an increase in stud strength with concrete strength for 3 in. deck, however, there were only a small number of tests performed on 3 in. deck. Because no tests were done on 3/8 in. diameter studs in 3 in. deck for concrete strengths other than 5240 psi, one cannot be certain if concrete strength affects the stud strength for this case.

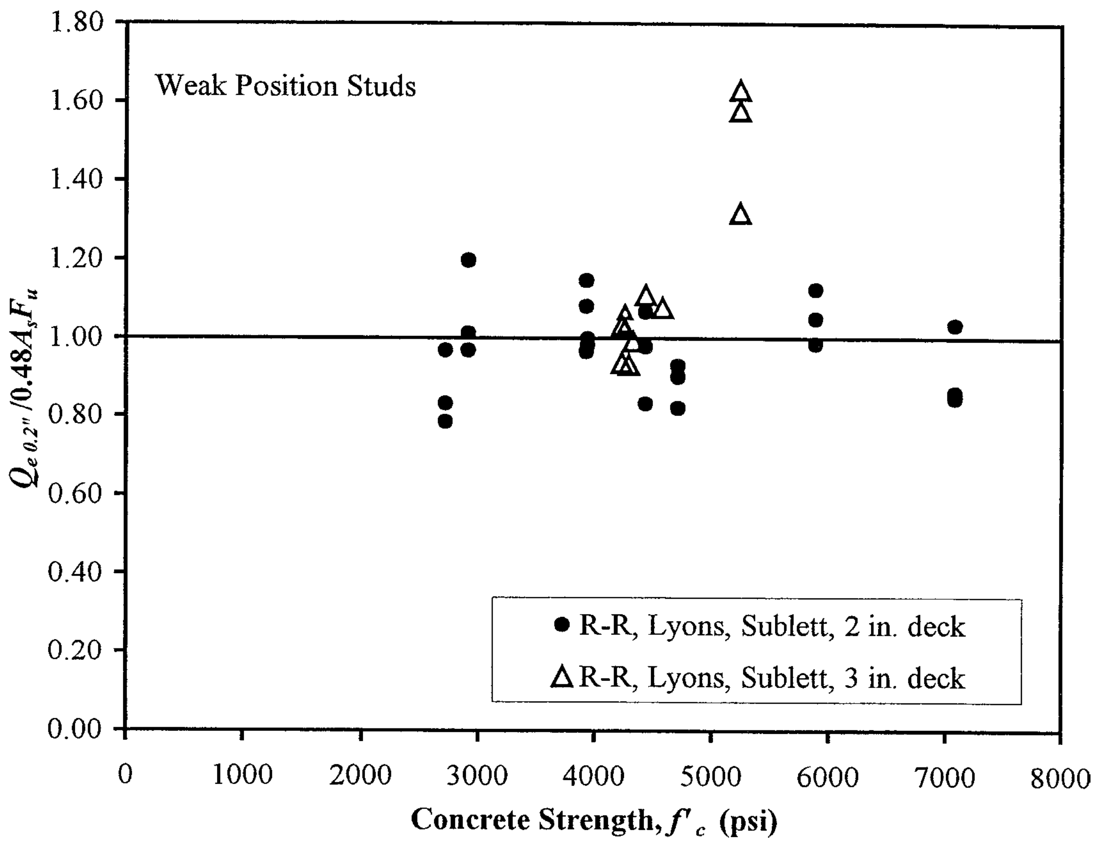

Fig. 6.5 Effect of Concrete Strength on Stud Strength of Single Weak Position Studs

Weak position studs have strengths of about $0.48A_sF_u$, lower than strong position studs because the studs are weakened by rib punching. The 3/8 in. diameter studs did not experience rib punching; the mode of failure was stud shearing, and so the strength of these studs is expected to be larger. The strength of weak position 3/8 in. diameter studs in 3 in. deck was closer to $0.72A_sF_u$. Even though the weak studs experienced stud shearing, they were still weaker than strong position 3/8 in. diameter studs in 3 in. deck, which had strengths around $0.92A_sF_u$. The strength of weak position 3/8 in. diameter studs in 2 in. deck was about $0.51A_sF_u$, less than $0.63A_sF_u$ if the studs were in the strong position.

To further test if the stud strength is dependent on the concrete strength, the data was all normalized to a concrete strength of 4000 psi by the following formula:

$$Q_{e\,norm} = Q_{e\,0.2"}\left(\frac{4000}{f_c^{'}}\right)^{0.5} \tag{6.5}$$

R dropped from 0.943 to 0.910 when this was done.

6.3.3 Modification for Different Gauge Deck

Also of interest to weak position studs is the effect of deck thickness. The tests used to develop Eqn. 6.4 all had 20 gauge deck. Lyons et al (1994) varied the deck thickness in tests on 3/4 in. diameter studs; the data from those tests is shown in Table 6.5.

It is shown in Fig. 6.6 that both the maximum strengths, Q_e, and the first peak strengths, $Q_{e\ 0.2"}$, increase with increasing deck thickness. Also, the ratios of $Q_e/Q_{e\ 0.2"}$ decrease with increasing deck thickness, as illustrated in Fig. 6.7. The peak load occurred at smaller amounts of slip for the thicker deck (16 and 18 gauge). The load was also more likely to drop off steadily for the thicker deck. For the 20 and 22 gauge deck, the load remained more constant and sometimes increased after 1 in. of slip.

Table 6.5 Effect of Deck Thickness on Ultimate and First Peak Strengths of Single Weak Position Studs

Program	Test	Deck Gauge	Deck Thickness (in.)	Q_e (k)	$Q_{e\,0.2''}$ (k)	$Q_e/Q_{e\,0.2''}$	$Q_{e\,ave.}$* (k)	$Q_{e\,0.2''\,ave.}$* (k)	$Q_{e\,ave.}/Q_{e\,0.2''\,ave.}$
Lyons	D40	22	0.0305	11.15	10.95	1.018	11.52	10.73	1.07
Lyons	D41	22	0.0305	10.96	10.96	1.000			
Lyons	D42	22	0.0305	12.46	10.29	1.211			
Lyons	D43	20	0.0362	11.56	11.09	1.042	12.67	12.17	1.04
Lyons	D44	20	0.0362	12.79	11.75	1.089			
Lyons	D45	20	0.0362	13.66	13.66	1.000			
Lyons	D46	18	0.0485	10.67	10.67	1.000	13.03	12.74	1.02
Lyons	D47	18	0.0485	14.8	14.19	1.043			
Lyons	D48	18	0.0485	13.62	13.36	1.019			
Lyons	D49	16	0.0603	15.06	15.02	1.003	13.60	13.48	1.01
Lyons	D50	16	0.0603	12.04	11.71	1.028			
Lyons	D51	16	0.0603	13.7	13.7	1.000			
* Average of the series									

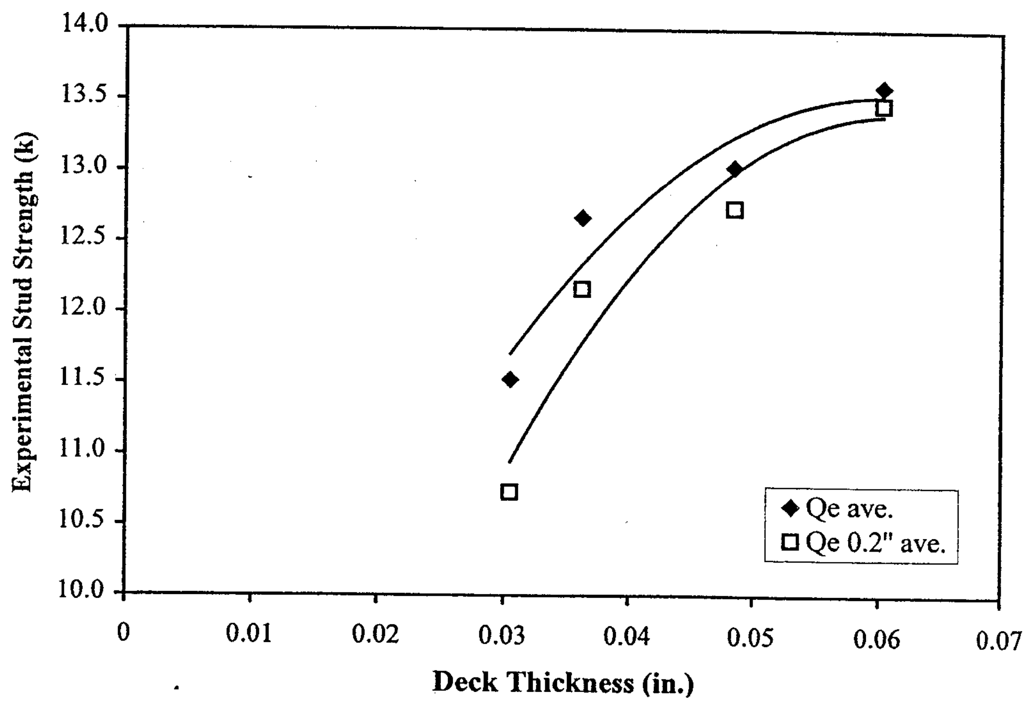

Fig. 6.6 Experimental Stud Strength vs. Deck Thickness For Single Weak Position Studs

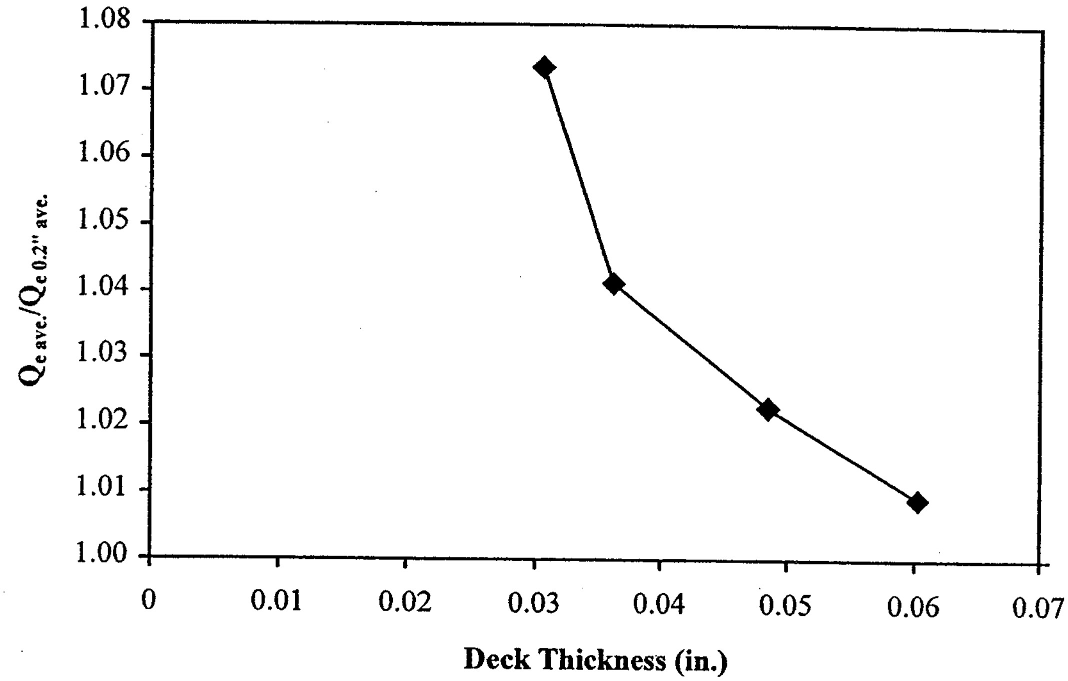

Fig. 6.7 Ratio of Maximum Strength-to-First Peak Load vs. Deck Thickness For Single Weak Position Studs

It was hoped that the tests using 20 gauge deck (Tests D43-D45) in Table 6.6 would have experimental strengths very close to the predicted strengths from Eqn. 6.5 so that a simple factor, equal to the ratio of the strengths from tests with other gauge deck to

Table 6.6 Effect of Deck Thickness on Predicted Strengths of Single Weak Position Studs

Program	Test	Deck Gauge	Deck Thickness (in.)	$Q_{e\ 0.2''}$ (k)	$0.48A_sF_u$ (k)	$Q_{e\ 0.2''}/0.48A_sF_u$	$Q_{e\ 0.2''\ ave.}$* (k)	$Q_{e\ 0.2''\ ave.}/0.48A_sF_u$*
Lyons	D40	22	0.0305	10.95	14.12	0.775	10.73	0.760
Lyons	D41	22	0.0305	10.96	14.12	0.776		
Lyons	D42	22	0.0305	10.29	14.12	0.729		
Lyons	D43	20	0.0362	11.09	14.12	0.785	12.17	0.862
Lyons	D44	20	0.0362	11.75	14.12	0.832		
Lyons	D45	20	0.0362	13.66	14.12	0.967		
Lyons	D46	18	0.0485	10.67	14.12	0.756	12.74	0.902
Lyons	D47	18	0.0485	14.19	14.12	1.005		
Lyons	D48	18	0.0485	13.36	14.12	0.946		
Lyons	D49	16	0.0603	15.02	14.12	1.064	13.48	0.954
Lyons	D50	16	0.0603	11.71	14.12	0.829		
Lyons	D51	16	0.0603	13.7	14.12	0.970		
* Average of the series								

the strength of the 20 gauge deck tests, could be applied to the strength prediction formula

$$Q_{1W} = 0.48 A_s F_u \tag{6.4}$$

for decks with gauges other than 20 gauge. However, the average experimental strength for the tests using 20 gauge deck was only 86% of the predicted strength. Because these were the only series of tests done on deck thicknesses other than 20 gauge, one may choose to apply the ratios just described for other deck thicknesses anyway. For example, the 22 gauge tests had an average strength of 10.73 k. The average strength for the 20 gauge tests was 12.17 k. Therefore, the strength of a stud welded to 22 gauge deck can be taken as

$$Q_{22\,ga.1W} = \frac{10.73}{12.17}\left(0.48 A_s F_u\right) = 0.88\left(0.48 A_s F_u\right) \tag{6.6}$$

because the portion $0.48A_sF_u$ of the equation above was developed based only on 20 gauge deck tests. So, a factor of 0.88 can be applied to the basic strength prediction equation (Eqn. 6.4) for weak position studs. Using the same procedure, the following formulas may be used to find the strength of a weak position stud in 18 gauge or 16 gauge deck.

$$Q_{20\,ga.1W} = 1.00\left(0.48 A_s F_u\right) \tag{6.7}$$

$$Q_{18\,ga.1W} = \frac{12.74}{12.17}\left(0.48 A_s F_u\right) = 1.05\left(0.48 A_s F_u\right) \tag{6.8}$$

$$Q_{16\,ga.1W} = \frac{13.48}{12.17}\left(0.48 A_s F_u\right) = 1.11\left(0.48 A_s F_u\right) \quad (6.9)$$

As mentioned previously, the tests in Table 6.6 were all on 3/4 in. diameter studs. The effect of deck strength on the strength of smaller diameter studs is probably less pronounced, although it was not specifically evaluated. There was no observed rib punching for 3/8 in. diameter studs, as mentioned previously.

6.3.4 Middle Position Single Studs in 1 in. and 1 1/2 in. Deck

Tests on single middle position studs from Sublett et al (1992) and Diaz et al (1998), with the exception of the tests discussed in Sections 3.4.3 – 3.4.5, were used in the development of a strength prediction model for single middle position studs. The tests done by Sublett et al (1992) on inverted deck were not used. All tests had $d/t \leq 2.7$, either 20 or 26 gauge deck, and either 1 in. or 1 1/2 in. deck. The influence of d/t will be discussed in Section 6.10.

After plotting the experimental strengths, Q_e, against each of the test variables, it was apparent that the strongest influence on stud strength for middle position studs in decks of 1 1/2 in. depth or less is the tensile strength of the stud, A_sF_u. A best-fit line, with a y-intercept of zero, was drawn through the data points in Fig. 6.8, giving a slope of 0.41. It can be shown that the coefficient 0.41 is not as suitable as the equation below, which would yield the same coefficient of correlation. The coefficient 0.48 was found by taking the average of the ratios Q_e/A_sF_u.

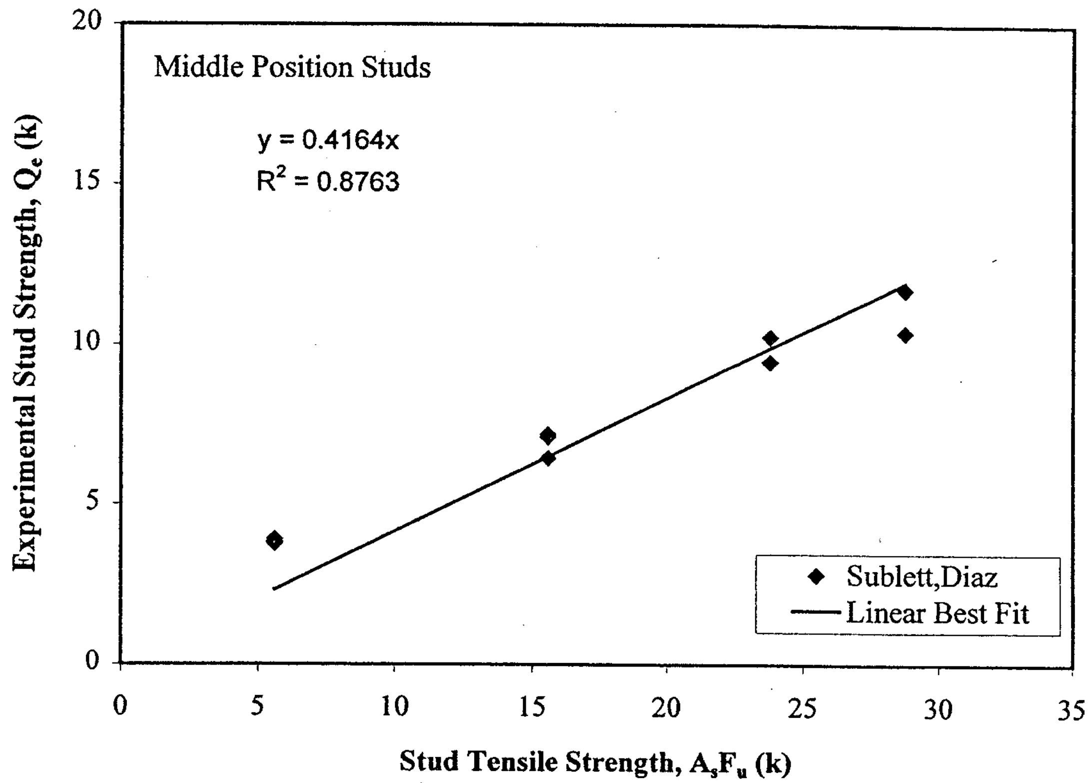

Fig. 6.8 Experimental Stud Strength vs. Stud Tensile Strength of Single Middle Position Studs

$$Q_{1M} = 0.48 A_s F_u \qquad (6.10)$$

These predicted strengths are compared to the experimental strengths in Table 6.7. The following statistics were calculated for Eqn. 6.10:

$R = 0.988$

Average ratio $Q_e/0.48A_sF_u = 1.027$

Minimum ratio $Q_e/0.68A_sF_u = 0.754$

Maximum ratio $Q_e/0.68A_sF_u = 1.462$

Coefficient of variation = 25.9 %

Table 6.7 Experimental and Predicted Strengths of Single Middle Position Studs

Program	Series	Test	$0.48A_sF_u$ (k)	Q_e (k)	$Q_e/0.48A_sF_u$	$Q_{e\ ave.}$ (k)	$Q_{e\ ave.}/0.48A_sF_u$
Sublett	5	5A	13.78	10.39	0.754	11.07	0.803
Sublett	5	5B	13.78	11.74	0.852		
Diaz	T2	T2-1	2.69	3.83	1.425	3.85	1.431
Diaz	T2	T2-2	2.69	3.78	1.406		
Diaz	T2	T2-3	2.69	3.93	1.462		
Diaz	T5	T5-1	7.47	7.09	0.949	6.90	0.924
Diaz	T5	T5-2	7.47	7.18	0.961		
Diaz	T5	T5-3	7.47	6.44	0.862		
Diaz	T8	T8-1	11.41	10.25	0.898	9.99	0.875
Diaz	T8	T8-2	11.41	9.46	0.829		
Diaz	T8	T8-3	11.41	10.25	0.898		

The scatter in the data in Fig. 6.8 is lessened if the averages of the experimental stud strengths for each series are used.

An even better fit was obtained with an exponential function, yielding the equation

$$Q_{1M} = 3.08e^{0.048A_sF_u} \tag{6.11}$$

for the strength of single middle position studs. These predicted strengths are compared to the experimental strengths in Table 6.8 and Fig. 6.9. The following statistics were calculated for Eqn. 6.11:

$R = 0.973$

Average ratio $Q_e / 3.08e^{0.048A_sF_u} = 0.997$

Table 6.8 Experimental and Predicted Strengths of Single Middle Position Studs (Exponential)

Program	Series	Test	Q_e (k)	$3.08e^{0.048AsFu}$ (k)	$Q_e/3.08e^{0.048AsFu}$	$Q_{e\,ave.}$ (k)	$Q_{e\,ave.}/3.08e^{0.048AsFu}$
Sublett	5	5A	10.39	12.221	0.850	11.07	0.905
Sublett	5	5B	11.74	12.221	0.961		
Diaz	T2	T2-1	3.83	4.030	0.950	3.85	0.955
Diaz	T2	T2-2	3.78	4.030	0.938		
Diaz	T2	T2-3	3.93	4.030	0.975		
Diaz	T5	T5-1	7.09	6.503	1.090	6.90	1.062
Diaz	T5	T5-2	7.18	6.503	1.104		
Diaz	T5	T5-3	6.44	6.503	0.990		
Diaz	T8	T8-1	10.25	9.642	1.063	9.99	1.036
Diaz	T8	T8-2	9.46	9.642	0.981		
Diaz	T8	T8-3	10.25	9.642	1.063		

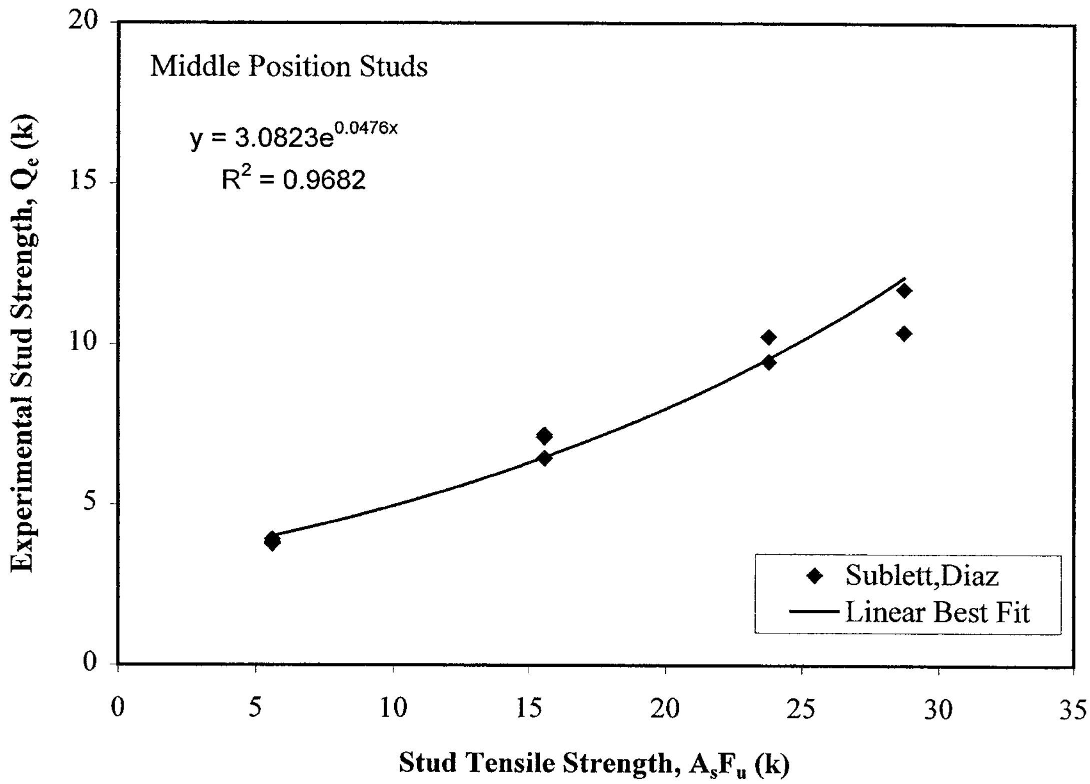

Fig. 6.9 Experimental Stud Strength vs. Stud Tensile Strength of Single Middle Position Studs (Exponential)

Minimum ratio $Q_e / 3.08e^{0.048 A_s F_u} = 0.850$

Maximum ratio $Q_e / 3.08e^{0.048 A_s F_u} = 1.104$

Coefficient of variation = 7.7%

This equation yields better predictions, but Eqn. 6.10 is more likely to be used in design.

6.4 New Definition of Strong and Weak Positions

Thus far, the position of the stud in the rib has been described as "strong" or "weak", depending on which side of the stiffener that the stud is welded, or as "middle" if the stud is welded centrally in the deck rib. In this section, a numerical definition of "strong" and "weak" positions is derived, depending on the value of $e_{mid\text{-}ht.}$, which is the distance from the center of the stud's longitudinal axis to the deck rib, at the mid-height of the rib, on the load bearing side of the stud.

All of the tests performed in this study and by Sublett et al (1992) and Lyons et al (1994) on strong position studs, which had strengths of about $0.68A_sF_u$, had an $e_{mid\text{-}ht.}$ value of approximately 4.5 in. All of the tests performed by these authors on weak position studs, which had strengths of about $0.48A_sF_u$, had an $e_{mid\text{-}ht.}$ value of approximately 1.5 in.

The middle position studs by Sublett et al (1992) and Diaz et al (1998) had $e_{mid\text{-}ht.}$ values of 0.92 in. for 1 in. deck; the middle position studs in 1 1/2 in. deck had $e_{mid\text{-}ht.}$ values of 1.06 in. The middle position studs had strengths of about $0.48A_sF_u$, which is the same as the strengths of the weak position studs. The similar values of $e_{mid\text{-}ht.}$ probably account for this similar strength.

It is important to be able to distinguish between a "strong" position stud and a "weak" position stud, especially since there is such a large difference in strength between the two positions.

Because limited values of $e_{mid\text{-}ht.}$ were used in the VT tests, the VT data can be supplemented by tests, with similar parameters, from other sources in order to determine the strength of studs with other $e_{mid\text{-}ht.}$ values. Table 6.9 shows test results from Robinson (1988) and Johnson and Yuan (1997), along with test results from VT. These results are

Table 6.9 Effect of Stud Position on Stud Strength

Program	Series	Deck Ht. (in.)	$e_{mid\text{-}ht.}$ (in.)	Q_e (k)	A_sF_u (k)	Q_e/A_sF_u
Rambo-Roddenberry	D12	2	1.5	14.25	29.08	0.490
Robinson (1988)	RI	2	2	18.7	NR	--
Johnson & Yuan (1997)	G2C	2.2	3.19	19.9	30.26	0.658
Rambo-Roddenberry	D10	2	4.5	20.18	29.08	0.694
Sublett et al (1992)	16	3	1.5	13.27	28.72	0.462
Robinson (1988)	QI	3	3	18.3	NR	--
Sublett et al (1992)	15	3	4.5	18.85	28.72	0.656
NR = Not Reported						

plotted in Fig. 6.10, and show that for $e_{mid\text{-}ht.}$ values below 2.2 in., the stud strength decreases very rapidly. With only a 0.7 in. decrease in concrete cover, the strength decreases from about $0.68A_sF_u$ to $0.48A_sF_u$. This difference in the amount of concrete

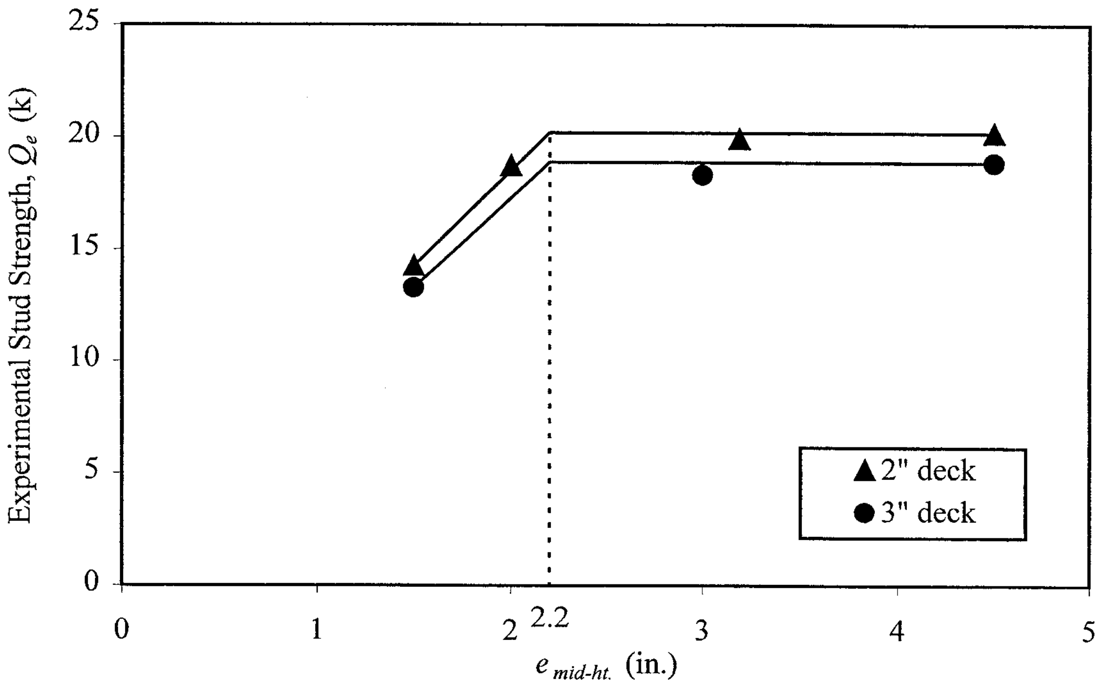

Fig. 6.10 Experimental Stud Strength vs. Stud Position

cover is not much when considering the care that it takes to weld the studs exactly where they are intended to be placed.

One could predict the strength of studs for $e_{mid\text{-}ht.} < 2.2$ in. from the following equation

$$Q_{e_{mid-ht}<2.2"} = (0.2e_{mid-ht.} + 0.18)A_s F_u \tag{6.12}$$

This equation would make the strength of a stud with $e_{mid\text{-}ht.}$ of 1.5 in. equal to $0.48A_sF_u$ (which is the strength of weak position studs tested at VT) and the strength of a stud with $e_{mid\text{-}ht.}$ of 4.5 in. equal to $0.68A_sF_u$ (which is the strength of strong position studs tested at VT).

This formula is verified by evaluating the tests from Sublett et al (1992) on single 3/4 in. diameter studs and tests from Jayas and Hosain (1988) on pairs of 5/8 in. diameter studs. Both of these authors performed tests on 1 1/2 in. deck in its normal position and in an inverted position; these two positions had different $e_{mid\text{-}ht.}$ values. All other parameters from each author's two series are similar. The test data is given in Table 6.10 and is shown graphically in Fig. 6.11. The studs are considered to be welded in the middle position because they are placed in the center of the deck ribs. However, the $e_{mid\text{-}ht.}$ values are all less than 2.2 in, giving them a "weak" position.

Table 6.10 Verification of New "Weak Position" Definition

Program	Series	Deck Ht. (in.)	$e_{mid\text{-}ht.}$ (in.)	Q_e (k)
Sublett et al (1992)	5	1.5	1.06	11.06
Sublett et al (1992)	6	1.5	1.94	18.43
Jayas and Hosain (1988)	JDT-3	1.5	1.2	8.41
Jayas and Hosain (1988)	JDT-4	1.5	1.8	12.1

Eqn. 6.12 was tested using Sublett's data. Interpolating the data for an $e_{mid\text{-}ht.}$ of 1.5 in., the strength is 14.7 k, or $0.51A_sF_u$ for an assumed F_u of 65 ksi. The coefficient 0.51 is reasonably close to the value of 0.48, which was calibrated with $e_{mid\text{-}ht.}$ of 1.5 in. Extrapolating the data for an $e_{mid\text{-}ht.}$ of 2.2 in., the strength is 20.6 k, or $0.72A_sF_u$ for an

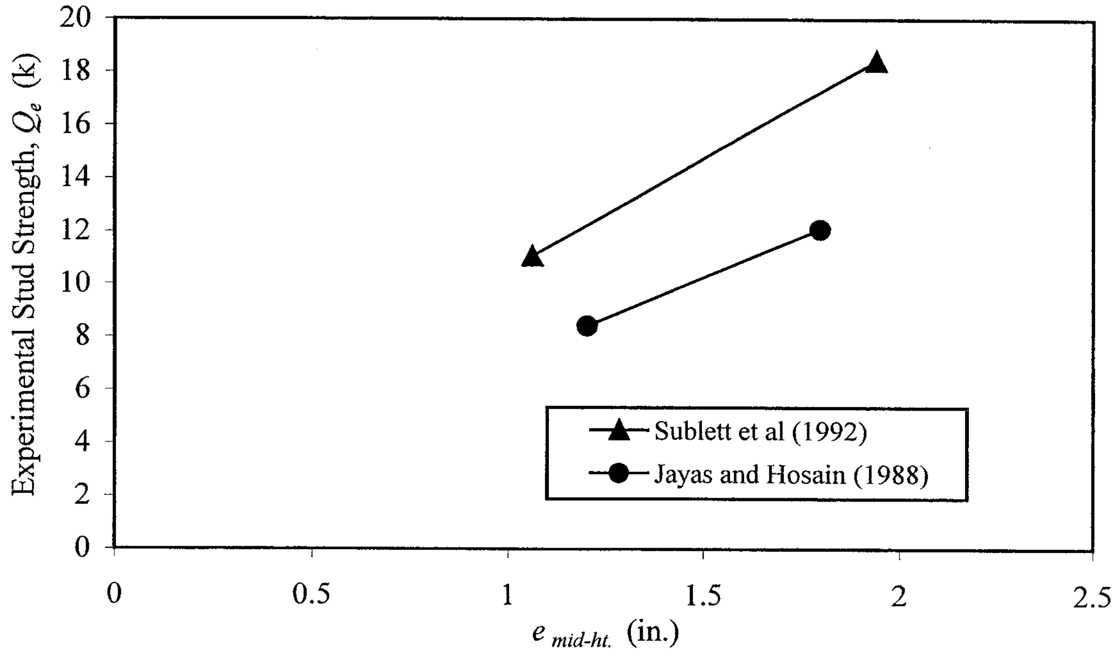

Fig. 6.11 Experimental Stud Strength vs. Concrete Cover

assumed value for F_u of 65 ksi. The coefficient 0.72 is reasonably close to the suggested value of 0.68 for $e_{mid\text{-}ht.} \geq 2.2$ in.

Notice from the tests by Jayas and Hosain (1988) that the strength of a stud increased from 8.41 k to 12.1 k (a 44% increase) with only a little more than 0.5 in. increase in concrete cover. Interpolating the data for an $e_{mid\text{-}ht.}$ of 1.5 in., the strength is 10.26 k, or $0.51A_sF_u$ for an assumed F_u of 65 ksi. For an $e_{mid\text{-}ht.}$ of 2.2 in., the extrapolated strength is 14.56 k, or $0.73A_sF_u$.

This data verifies the accuracy of Eqn. 6.12. However, because such a large reduction in stud strength occurs with only a small decrease in concrete cover in front of the stud for $e_{mid\text{-}ht.}$ < 2.2 in., it is recommended that the strength of a single stud with $e_{mid\text{-}ht.}$ < 2.2 in. be taken as the weak position stud strength, $0.48A_sF_u$. When $e_{mid\text{-}ht.} \geq 2.2$ in., the strength can be taken as the strong position stud strength, $0.68A_sF_u$. This has been confirmed using data from tests on 1 in., 1 1/2 in., 2 in., and 3 in. deck.

6.5 Multiple Studs per Rib

6.5.1 Staggered Position Studs in 2 in. and 3 in. Deck

Several push-out tests were done by Lyons et al (1994) on staggered position studs. The staggered position refers to two studs welded in the same rib, with one stud in the strong position and one stud in the weak position. They are welded on opposite sides of the beam web, approximately midway between the web and flange tip. These tests were all on 3/4 in. diameter studs with approximately the same measured value of A_sF_u. Because of this, it is not beneficial to use the same procedure that was used with strong and weak position studs to find a suitable strength prediction model. It is best to compare these tests to tests with similar parameters done on single strong position 3/4 in. diameter studs. The tests that are compared (i.e., Lyons Series 2 is compared to Lyons Series 10) have the same parameters, except f'_c varies slightly.

Tests on strong position studs are compared to tests on staggered studs in Table 6.11, which shows that staggered studs consistently exhibit lower strengths than strong position studs. For the tests in 2 in. deck, the average ratio of $Q_{e\ Strong}/Q_{e\ Stag}$ = 0.740, the minimum ratio is 0.673, the maximum ratio is 0.777, and the coefficient of variation is 6.6%. For the tests in 3 in. deck, the average ratio of $Q_{e\ Strong}/Q_{e\ Stag}$ = 0.805, the minimum

Table 6.11 Staggered Position and Single Strong Position Stud Strengths

	Program	Series	Test	Stud Position	Stud Ht. (in.)	$Q_{e\ Strong}$ (k)	$Q_{e\ Stag}$ (k)	$Q_{e\ Stag}$/ $Q_{e\ Strong}$
2" Deck	Lyons	1	D2	S	3.5	21.91		0.74
	Lyons	1	D3	S	3.5	18.08		
	Lyons	24	D61	STAG	3.5		14.13	
	Lyons	24	D62	STAG	3.5		15.32	
	Lyons	24	D63	STAG	3.5		14.81	
	Lyons	2	D4	S	4	19.44		0.78
	Lyons	2	D5	S	4	18.85		
	Lyons	2	D6	S	4	20.73		
	Lyons	10	D19	STAG	4		15.49	
	Lyons	10	D20	STAG	4		15.28	
	Lyons	10	D21	STAG	4		15.11	
	Lyons	3	D7	S	4.5	21.18		0.77
	Lyons	3	D8	S	4.5	20.37		
	Lyons	3	D9	S	4.5	21.46		
	Lyons	25	D79	STAG	4.5		16.13	
	Lyons	25	D80	STAG	4.5		15.50	
	Lyons	25	D81	STAG	4.5		17.10	
	Lyons	4	D10	S	5	20.62		0.67
	Lyons	4	D11	S	5	21.02		
	Lyons	4	D12	S	5	21.97		
	Lyons	26	D70	STAG	5		14.01	
	Lyons	26	D71	STAG	5		15.21	
	Lyons	26	D72	STAG	5		13.56	
3" Deck	Lyons	6	D52	S	4.5	17.39		0.85
	Lyons	6	D53	S	4.5	14.61		
	Lyons	6	D54	S	4.5	18.35		
	Lyons	13	D76	STAG	4.5		13.34	
	Lyons	13	D77	STAG	4.5		14.95	
	Lyons	13	D78	STAG	4.5		14.50	
	Lyons	7	D55	S	5	18.21		0.78
	Lyons	7	D56	S	5	15.49		
	Lyons	7	D57	S	5	18.30		
	Lyons	14	D64	STAG	5		13.70	
	Lyons	14	D65	STAG	5		14.12	
	Lyons	14	D66	STAG	5		12.51	
	Lyons	8	D58	S	5.5	18.67		0.79
	Lyons	8	D59	S	5.5	19.60		
	Lyons	8	D60	S	5.5	17.45		
	Lyons	15	D67	STAG	5.5		14.02	
	Lyons	15	D68	STAG	5.5		14.96	
	Lyons	15	D69	STAG	5.5		14.94	

ratio is 0.776, the maximum ratio is 0.850, and the coefficient of variation is 4.9%. The average ratio of all tests is 0.768. If this ratio is applied to the strength prediction equation for single strong position studs, the equation to predict the strength of a staggered stud becomes

$$Q_{Stag} = 0.768(0.68A_sF_u) = 0.52A_sF_u \tag{6.13}$$

This equation should be used for both the strong position stud and the weak position stud. This strength is slightly higher than the strength of a single weak position stud.

6.5.2 Pairs of Strong Position Studs

When there are multiple studs in a rib, and the studs are placed side-by-side, perpendicular to the direction of load, there may be a reduction in the strength from the strength of a stud placed in the single position. To investigate the effect of placing a strong stud in a pair with another strong stud, tests performed at VT by Lyons et al (1994) on single studs are compared to tests on pairs of strong position studs in Table 6.12. These tests all had 3/4 in. diameter studs in 2 in. deck. Each set of two series that are compared (i.e., Lyons Series 3 is compared to Lyons Series 29) has identical parameters except for the number of studs per rib and the concrete strength. The average ratio, for the four sets of compared series, of $Q_{e2Strong}/Q_{eStrong}$ = 0.844. Table 6.13 makes the same comparison for tests performed at VT, on different diameter studs in 2 in. deck, in this study. The average ratio for these tests of $Q_{e2Strong}/Q_{eStrong}$ = 1.03.

Table 6.12 Strengths of Single and Pairs of Strong Position Studs (Lyons' Tests)

Program	Series	Test	Stud Position	Stud Dia. (in.)	Stud Ht. (in.)	f'c (psi)	$Q_{e\ Strong}$ (k)	$Q_{e\ 2Strong}$ (k)	$Q_{e\ 2Strong}/Q_{e\ Strong}$
Lyons	1	D2	S	0.750	3.5	4560	21.91		0.77
Lyons	1	D3	S	0.750	3.5	4560	18.08		
Lyons	27	D73	2S	0.750	3.5	2670		15.79	
Lyons	27	D74	2S	0.750	3.5	2670		14.99	
Lyons	27	D75	2S	0.750	3.5	2670		15.61	
Lyons	2	D4	S	0.750	4	4560	19.44		0.88
Lyons	2	D5	S	0.750	4	4560	18.85		
Lyons	2	D6	S	0.750	4	4560	20.73		
Lyons	28	D82	2S	0.750	4	3650		16.92	
Lyons	28	D83	2S	0.750	4	3650		19.42	
Lyons	28	D84	2S	0.750	4	3650		15.53	
Lyons	3	D7	S	0.750	4.5	4560	21.18		0.96
Lyons	3	D8	S	0.750	4.5	4560	20.37		
Lyons	3	D9	S	0.750	4.5	4560	21.46		
Lyons	29	D85	2S	0.750	4.5	3650		18.88	
Lyons	29	D86	2S	0.750	4.5	3650		20.92	
Lyons	29	D87	2S	0.750	4.5	3650		20.67	
Lyons	4	D10	S	0.750	5	4560	20.62		0.77
Lyons	4	D11	S	0.750	5	4560	21.02		
Lyons	4	D12	S	0.750	5	4560	21.97		
Lyons	19	D37	2S	0.750	5	3520		16.52	
Lyons	19	D38	2S	0.750	5	3520		17.76	
Lyons	19	D39	2S	0.750	5	3520		14.43	

It is important to note that the series that are compared to each other in Lyons et al (1994) have different concrete strengths (i.e., Series 3 has 4560 psi concrete, while Series 29 has 3650 psi concrete). Every series of tests by Lyons on pairs of studs has a lower concrete strength than its accompanying series of tests on single studs. This may contribute to the lower strengths of studs in pairs than of single studs in Lyons' tests. As discussed in Section 6.6.1, it is believed that concrete strength may affect the strength of a stud in a pair. The series that are compared to each other from the tests in this study (Rambo-Roddenberry et al 2002) have the same concrete strength and also have virtually the same stud strength. There is no reduction in strength for a stud placed in a pair in the tests in this study.

Table 6.13 Strengths of Single and Pairs of Strong Position Studs

Program	Series	Test	Stud Position	Stud Dia. (in.)	Stud Ht. (in.)	f'c (psi)	$Q_{e\ Strong}$ (k)	$Q_{e\ 2Strong}$ (k)	$Q_{e\ 2Strong}/Q_{e\ Strong}$
Rambo-Roddenberry	D1	D1	S	0.500	4	4430	9.77		0.95
Rambo-Roddenberry	D1	D2	S	0.500	4	4430	7.29		
Rambo-Roddenberry	D1	D3	S	0.500	4	4430	9.23		
Rambo-Roddenberry	D2	D4	2S	0.500	4	4430		8.95	
Rambo-Roddenberry	D2	D5	2S	0.500	4	4430		8.76	
Rambo-Roddenberry	D2	D6	2S	0.500	4	4430		7.16	
Rambo-Roddenberry	D4	D10	S	0.625	4	2915	12.53		0.98
Rambo-Roddenberry	D4	D11	S	0.625	4	2915	13.54		
Rambo-Roddenberry	D4	D12	S	0.625	4	2915	15.55		
Rambo-Roddenberry	D6	D16	2S	0.625	4	2915		11.87	
Rambo-Roddenberry	D6	D17	2S	0.625	4	2915		15.42	
Rambo-Roddenberry	D7	D19	S	0.500	4	5890	8.86		1.26
Rambo-Roddenberry	D7	D20	S	0.500	4	5890	9.14		
Rambo-Roddenberry	D7	D21	S	0.500	4	5890	6.63		
Rambo-Roddenberry	D8	D22	2S	0.500	4	5890		9.23	
Rambo-Roddenberry	D8	D23	2S	0.500	4	5890		10.30	
Rambo-Roddenberry	D8	D24	2S	0.500	4	5890		11.46	
Rambo-Roddenberry	D10	D28	S	0.750	4	7080	20.01		0.95
Rambo-Roddenberry	D10	D29	S	0.750	4	7080	18.72		
Rambo-Roddenberry	D10	D30	S	0.750	4	7080	21.80		
Rambo-Roddenberry	D11	D32	2S	0.750	4	7080		17.49	
Rambo-Roddenberry	D11	D33	2S	0.750	4	7080		20.89	
Rambo-Roddenberry	D13	D37	S	0.625	4	4710	16.18		1.03
Rambo-Roddenberry	D13	D38	S	0.625	4	4710	17.07		
Rambo-Roddenberry	D13	D39	S	0.625	4	4710	14.53		
Rambo-Roddenberry	D14	D40	2S	0.625	4	4710		14.70	
Rambo-Roddenberry	D14	D41	2S	0.625	4	4710		16.95	
Rambo-Roddenberry	D14	D42	2S	0.625	4	4710		17.43	

Current AISC specifications call for the factor $1/\sqrt{N}$, where $N = 2$ for a pair of studs, to be applied to the strength of a single stud to predict the strength of a stud in a pair, if Eqn. 4.2 for the *SRF* governs the strength. This predicts that a stud in a pair, depending on the combination of parameters, sometimes is only 71% of the strength of a single stud. From the comparisons made in Tables 6.12 and 6.13, a factor around 0.85 seems reasonable. Hence, the strength of a stud placed in a pair with another strong position stud can be taken as

$$Q_{2S} = 0.85_{Q1S} = 0.85(0.68A_sF_u) \tag{6.14}$$

There were no tests done at VT on pairs of strong position studs in 3 in. deck.

6.5.3 Pairs of Middle Position Studs

Tests on 3/8 in. and 1/2 in. diameter studs placed in the middle position in 1 in. deck are summarized in Table 6.14. The series that are compared to each other in this

Table 6.14 Strengths of Single and Pairs of Middle Position Studs (Diaz's Tests)

Program	Series	Test	Stud Position	Stud Dia. (in.)	Stud Ht. (in.)	f'_c (psi)	$Q_{e\,Middle}$ (k)	$Q_{e\,2Middle}$ (k)	$Q_{e\,2Middle}$/ $Q_{e\,Middle}$
Diaz	T2	T2-1	M	0.375	2.5	4950	3.83		0.91
Diaz	T2	T2-2	M	0.375	2.5	4950	3.78		
Diaz	T2	T2-3	M	0.375	2.5	4950	3.93		
Diaz	T3	T3-1	2M	0.375	2.5	4950		3.38	
Diaz	T3	T3-2	2M	0.375	2.5	4950		3.48	
Diaz	T3	T3-3	2M	0.375	2.5	4950		3.60	
Diaz	T5	T5-1	M	0.5	2.5	4850	7.09		0.80
Diaz	T5	T5-2	M	0.5	2.5	4850	7.18		
Diaz	T5	T5-3	M	0.5	2.5	4850	6.44		
Diaz	T6	T6-1	2M	0.5	2.5	4900		5.88	
Diaz	T6	T6-2	2M	0.5	2.5	4900		5.50	
Diaz	T6	T6-3	2M	0.5	2.5	4900		5.28	

table have virtually the same concrete strength, yet studs placed in pairs are weaker than single studs. These studs were in the "middle" position of 1 in. deck, which means they have much less concrete cover in front of the stud base than the strong position studs discussed in the previous section. This may cause a reduction in strength for pairs of weak position studs because there is much less concrete to carry the load of two studs.

This eventually results in an increase in the distance from the base of the stud of the resultant force on the stud, which decreases the stud strength.

The average ratio of $Q_{e2Middle}/Q_{e1Middle}$ is 0.85 from the tests in Table 6.14. The strength of a stud placed in a pair with another stud placed in the middle of the rib would be 85% of the strength of a single middle position stud, which is

$$Q_{2M} = 0.85Q_{1M} = 0.85(0.48A_sF_u) \tag{6.15}$$

6.5.4 Other Tests on Pairs of Studs

Robinson (1988) performed tests on single and pairs of studs and found that there is a significant reduction in strength when a stud is placed in a pair with another stud. The strength of a stud in a pair ranged from 49% to 90% of the strength of a single stud, as seen in Table 6.15. Jayas and Hosain (1988) found similar results. These tests all had similar concrete strengths (from 3205 psi to 3610 psi) and similar transverse stud spacings (3 1/2 in. or 4 in.)

Table 6.15 Strengths of Pairs of Studs and Single Studs Using Other Data

Program	Series	Stud Position	Deck Ht. (in.)	Stud Dia. (in.)	No. Studs Per Rib	Q_e (k)	$Q_{e\,Pair}/Q_{e\,Single}$
Robinson (1988)	QI	M ($e_{mid\,ht.}$=3")	3	0.750	1	18.30	0.66
Robinson (1988)	QII	M ($e_{mid\,ht.}$=3")	3	0.750	2	12.00	
Robinson (1988)	RI	M ($e_{mid\,ht.}$=2")	2	0.750	1	18.70	0.90
Robinson (1988)	RII	M ($e_{mid\,ht.}$=2")	2	0.750	2	16.80	
Robinson (1988)	TI	S ($e_{mid\,ht.}$=5.6")	3	0.750	1	23.70	0.61
Robinson (1988)	TII	S ($e_{mid\,ht.}$=5.6")	3	0.750	2	14.50	
Robinson (1988)	TVII	W ($e_{mid\,ht.}$=1.5")	3	0.750	1	21.90	0.49
Robinson (1988)	TVIII	W ($e_{mid\,ht.}$=1.5")	3	0.750	2	10.70	
Jayas and Hosain (1988)	JDT-8	S ($e_{mid\,ht.}$=4.5"?)	3	0.750	1	16.70	0.62
Jayas and Hosain (1988)	JDT-7	S ($e_{mid\,ht.}$=4.5"?)	3	0.750	2	10.36	

6.6 Concrete Strength

6.6.1 Effect of Concrete Strength on Stud Strength

The effect of concrete strength on the strength of studs in solid slabs is well documented (Ollgaard et al 1971). Oehlers and Johnson (1987) stated that "increasing the strength of the stud will allow the concrete to resist a greater shear load as the interface pressure can be distributed across a larger area before fracture of the stud, whereas increasing the strength of the concrete, and hence its modulus, will reduce the flexural forces on the stud and allow a greater shear load before fracture of the stud." The results of tests at VT show that concrete strength may not be very influential on the strength of a stud positioned in deck that is perpendicular to the beam to which the stud is welded. It seems that studs placed in deck are much more dependent on the *amount* of concrete between the stud and deck rib near the base of the stud, which is not accounted for in the AISC equations, than on the *strength* of the concrete.

Series of tests that have identical parameters, except for concrete strength, are compared in Table 6.16 and are shown graphically in Fig. 6.12. It appears that there is no influence of concrete strength on stud strength for single studs in the strong or weak positions ("S" or "W" stud positions). However, for strong position studs placed in pairs ("2S" stud position), the stud strength increases with concrete strength. This is supported by observations made in Section 6.5.2. For example, Lyons Series 17, which used strong studs in pairs and a concrete strength of 3520 psi, had an average stud strength of 15 k; the stud strength increases to 19.2 k when the concrete strength is 7080 psi (Series D11 in this study). There is not a change in strength for single studs: Lyons Series 2 had a

Table 6.16 Effect of Concrete Strength on Stud Strength

Program	Series	Stud Position	Stud Dia. (in.)	Stud Ht. (in.)	f'_c (psi)	$Q_{e\ ave.}$ (k) or $Q_{e\ 0.2''\ ave.}$ (k)*
Rambo-Roddenberry	D4	S	0.625	4	2915	13.9
Rambo-Roddenberry	D13	S	0.625	4	4710	15.9
Rambo-Roddenberry	D1	S	0.5	4	4430	8.76
Rambo-Roddenberry	D7	S	0.5	4	5890	8.21
Lyons	2	S	0.75	4	4560	19.7
Rambo-Roddenberry	D10	S	0.75	4	7080	20.2
Rambo-Roddenberry	D5	W	0.625	3.5	2915	10.5
Rambo-Roddenberry	D15	W	0.625	4	4710	9.45
Rambo-Roddenberry	D3	W	0.5	4	4430	6.69
Rambo-Roddenberry	D9	W	0.5	4	5890	7.35
Lyons	21	W	0.75	3.5	2720	12.2
Rambo-Roddenberry	D12	W	0.75	4	7080	12.7
Rambo-Roddenberry	D6	2S	0.625	4	2915	13.6
Rambo-Roddenberry	D14	2S	0.625	4	4710	16.4
Rambo-Roddenberry	D2	2S	0.5	4	4430	8.29
Rambo-Roddenberry	D8	2S	0.5	4	5890	10.3
Lyons	17	2S	0.75	4	3520	15.0
Rambo-Roddenberry	D11	2S	0.75	4	7080	19.2

2 in. deck used in all tests

* $Q_{e\ ave.}$ is used for S and 2S position studs

$Q_{e\ 0.2''\ ave.}$ is used for W position studs

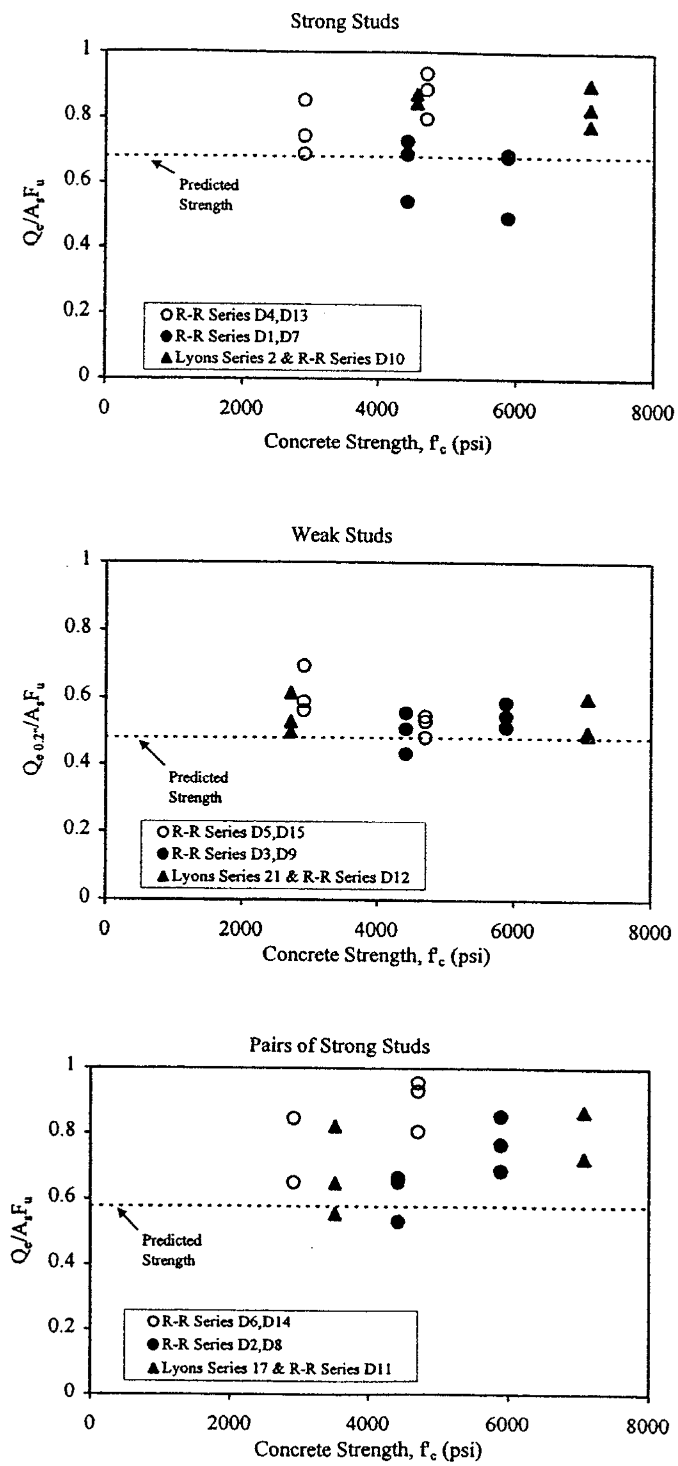

Fig. 6.12 Stud Strength vs. Concrete Strength

single strong position stud strength of 19.7 k with a concrete strength of 4560 psi. The strength only increases by 0.5 k to 20.2 k for a concrete strength of 7080 psi; this difference could easily be due to variability in the data.

6.6.2 Effect of Concrete Strength on Elastic Stiffness

The concrete strength seems to affect the elastic stiffness of the studs as shown in Table 6.17. The load-slip data, using the tests from the series that were compared in Table 6.16, was analyzed for the initial stages of loading (up to about 20 k total load, i.e. 5 k per stud). The only parameter that varied was concrete strength, for each two series compared (Series D1 and Series D7 are two series from this study that are compared). The stud height was varied somewhat between some of the series. However, this effect is negligible because the studs were all at least 1 1/2 in. above the top of the deck. The total load was divided by the average of the slips for the initial portion of the load-slip diagram, while the specimen was still elastic. The values for the stiffnesses appear difficult to predict. However, overall the increase in concrete strength causes an increase in the elastic stiffness of the studs (i.e., the studs will deform less when subjected to low loads when they are surrounded by strong concrete). Table 6.17 also shows that weak studs are not as stiff as strong studs, as expected.

Table 6.17 Effect of Concrete Strength on Elastic Stiffness of Studs

	Program	Series	Test	Total Load [T.L.] (k)	Slip* (in.)	T.L./Slip (k/in.)	Ave. T.L./Slip (k/in.)	f'_c (psi)
Strong Studs	Rambo-Roddenberry	D4	D10	20.60	0.0046	4478	4322	2915
	Rambo-Roddenberry	D4	D11	21.23	0.0066	3217		
	Rambo-Roddenberry	D4	D12	21.61	0.0041	5271		
	Rambo-Roddenberry	D13	D37	29.02	0.0054	5374	7350	4710
	Rambo-Roddenberry	D13	D38	29.84	0.0032	9325		
	Rambo-Roddenberry	D13	D39	?	?	--		
	Rambo-Roddenberry	D1	D1	16.71	0.0055	3038	2498	4430
	Rambo-Roddenberry	D1	D2	10.18	0.0052	1958		
	Rambo-Roddenberry	D1	D3	?	?	--		
	Rambo-Roddenberry	D7	D19	16.33	0.0040	4083	4778	5890
	Rambo-Roddenberry	D7	D20	9.92	0.0025	3968		
	Rambo-Roddenberry	D7	D21	10.68	0.0017	6282		
	Lyons	2	D4	25.02	0.0053	4721	6257	4563
	Lyons	2	D5	20.18	0.0026	7762		
	Lyons	2	D6	25.15	0.0040	6288		
	Rambo-Roddenberry	D10	D28	40.45	0.0026	15558	8932	7080
	Rambo-Roddenberry	D10	D29	20.35	0.0029	7017		
	Rambo-Roddenberry	D10	D30	25.75	0.0061	4221		
Weak Studs	Rambo-Roddenberry	D5	D13	15.08	0.0064	2356	2122	2915
	Rambo-Roddenberry	D5	D14	16.21	0.0060	2702		
	Rambo-Roddenberry	D5	D15	15.83	0.0121	1308		
	Rambo-Roddenberry	D15	D43	16.39	0.0099	1656	2212	4710
	Rambo-Roddenberry	D15	D44	16.46	0.0085	1936		
	Rambo-Roddenberry	D15	D45	17.96	0.0059	3044		
	Rambo-Roddenberry	D3	D7	14.82	0.0098	1512	1847	4430
	Rambo-Roddenberry	D3	D8	14.57	0.0043	3388		
	Rambo-Roddenberry	D3	D9	9.30	0.0145	641		
	Rambo-Roddenberry	D9	D25	15.33	0.0034	4509	3790	5890
	Rambo-Roddenberry	D9	D26	15.20	0.0032	4750		
	Rambo-Roddenberry	D9	D27	16.46	0.0078	2110		
	Lyons	21	D43	21.15	0.0180	1175	1883	2716
	Lyons	21	D44	21.30	0.0101	2109		
	Lyons	21	D45	21.28	0.0090	2364		
	Rambo-Roddenberry	D12	D34	19.97	0.0076	2628	3545	7080
	Rambo-Roddenberry	D12	D35	19.97	0.0061	3274		
	Rambo-Roddenberry	D12	D36	20.35	0.0043	4733		

* Average of all slip readings

6.7 Deck Height

Current strength prediction equations for studs welded through deck include the deck height as a parameter. Tests at VT show that the deck height is not as influential on stud strength as the amount of concrete between the stud and deck rib ($e_{mid\text{-}ht.}$). Table 6.18 compares similar series of tests where the deck height and concrete strength were

Table 6.18 Effect of Deck Height on Stud Strength

Program	Series	Deck Ht. (in.)	f'_c (psi)	Stud Dia. (in.)	Stud Ht. (in.)	Stud Position	$Q_{e\ ave.}$ or $Q_{e\ 0.2''\ ave.}$*	Inc. or Dec. in Qe w/ Inc. Deck Ht.?
Rambo-Roddenberry	D16	2	3930	0.375	4	S	5.48	Increase
Rambo-Roddenberry	D20	3	5240	0.375	5	S	7.88	
Rambo-Roddenberry	D18	2	3930	0.375	4	W	4.47	Increase
Rambo-Roddenberry	D22	3	5240	0.375	5	W	6.18	
Rambo-Roddenberry	D10	2	7080	0.75	4	S	20.2	Decrease
Sublett	15	3	4630	0.75	5	S	18.8	
Rambo-Roddenberry	D12	2	7080	0.75	4	W	12.7	Increase
Sublett	16	3	4305	0.75	5	W	13.3	
Sublett	3	2	4085	0.75	3.5	S	18.9	Increase
Sublett	1	3	4007	0.75	5	S	19.6	
Sublett	4	2	3939	0.75	3.5	W	13.6	Increase
Sublett	2	3	4257	0.75	5	W	14.5	
Sublett	14	2	4805	0.75	3.5	S	22.7	Decrease
Sublett	13	3	4445	0.75	5	S	19.4	
Lyons	2	2	4560	0.75	4	S	19.7	Decrease
Lyons	7	3	3360	0.75	5	S	17.3	
Lyons	10	2	3240	0.75	4	Stag	15.3	Decrease
Lyons	14	3	2670	0.75	5	Stag	13.4	

* $Q_{e\ ave.}$ used for S and Stag Stud Positions
$Q_{e\ 0.2''\ ave.}$ used for W Stud Positions

varied. All tests used 20 gauge deck, except for Lyons Series 2 and Lyons Series 10, which both used 22 gauge deck. (Because the deck height varied, the stud height also varied so that the stud would be a minimum of 1 1/2 in. above the top of the deck).

For example, comparing Sublett Series 3 to Sublett Series 1, a slight increase in stud strength occurred with an increase in deck height from 2 in. to 3 in. The right hand column of Table 6.18 indicates that the deck height does not consistently affect stud strength.

6.8 Stud Height

Several push-out tests by Lyons et al (1994) can be used to investigate the effect of the stud height on strength. A summary of these tests, all of which were on 3/4 in. diameter studs, is given in Table 6.19. Experimental strengths given are averages from

Table 6.19 Effect of Stud Height on Stud Strength (Lyons' Tests)

h_R (in.)	Stud Position	H_s (in.)	H_s/h_R	f'_c (psi)	$Q_{e\ ave.}$ (k)
2	S	3.5	1.75	4563	20
		4	2.00	4563	19.7
		4.5	2.25	4563	21
		5	2.50	4563	21.2
		5.5	2.75	4563	20.5
2	Stag	3.5	1.75	3362	14.7
		4	2.00	3326	15.3
		4.5	2.25	3653	16.2
		5	2.50	2674/3326	14.6
2	2S	3.5	1.75	2674/3515	15.6
		4	2.00	3515/3653	17.5
		4.5	2.25	3515/3653	18.6
		5	2.50	3515	17.2
3	S	4.5	1.50	3362	17.9
		5	1.67	3362	18.3
		5.5	1.83	3362	18.6
3	Stag	4.5	1.50	3653	14.3
		5	1.67	2674	13.4
		5.5	1.83	2674	14.6

all of the tests done on a given set of parameters. The data is first arranged according to stud position and deck height, then by stud height. From a plot of the data, as shown in Fig. 6.13, it appears that there is an increase in stud strength with an increase in stud height until the ratio of H_s/h_R is about 2.3. The same trend is noticed when all of the data is normalized to a concrete strength of 3500 psi.

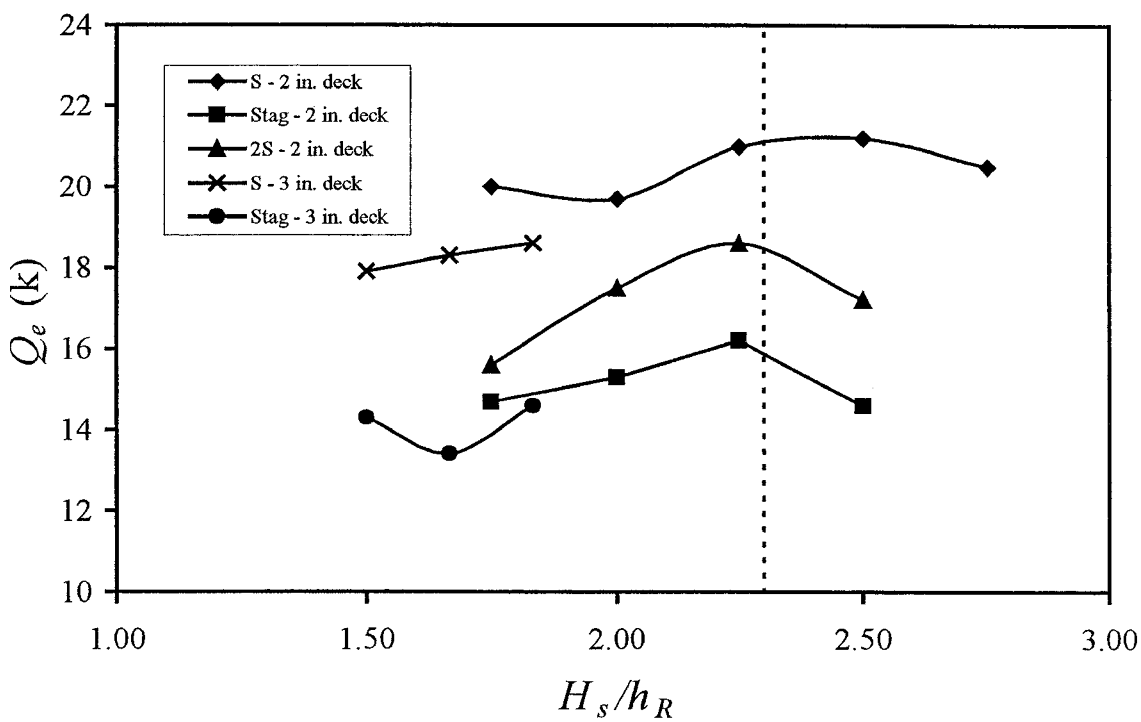

Fig. 6.13 Experimental Stud Strength vs. Ratio of Stud Height-to-Rib Height

Because push-out tests show that there is not a significant increase in strength with an increase in stud height, and because the tendency in design is to use the minimum stud height allowed, the height of a stud should not be a parameter in the new strength prediction method.

6.9 Normal Load

6.9.1 Effect of Normal Load on Stud Strength

Push-out tests performed at VT on composite slabs usually had a normal load applied to the concrete slabs of the specimens and perpendicular to the longitudinal axis of the beams. Tests were done on solid slabs where either no normal load was used or a normal load equal to 10% of the axial load was used. It was found in Section 3.3.3 that this normal load influenced stud strength for solid slab specimens.

Tests were also done on composite slab specimens where the normal load was varied from 5% to 20%. These tests are reported graphically in Fig. 6.14. It appears that there is not a predictable influence on stud strength of the applied normal load. The tests do show, however, that using only a 5% normal load causes a lot of variability in stud strength. A few of the tests in this study that used only 5% normal load were not used in the evaluation of test results because inexplicably low strengths were obtained. This is probably because the specimens are allowed to "peel apart" when little or no normal load is used, resulting in lower strengths. This problem is inherent only in push-out tests and does not occur in beam tests.

6.9.2 Effect of Normal Load on Elastic Stiffness

The amount of normal load applied seems to affect the elastic stiffness of the specimens. This was noticed when specimens which had 20% normal load exhibited very little slip, even at large loads. Table 6.20 compares the elastic stiffnesses of similar series of tests where only normal load was varied. Concrete strengths varied a little

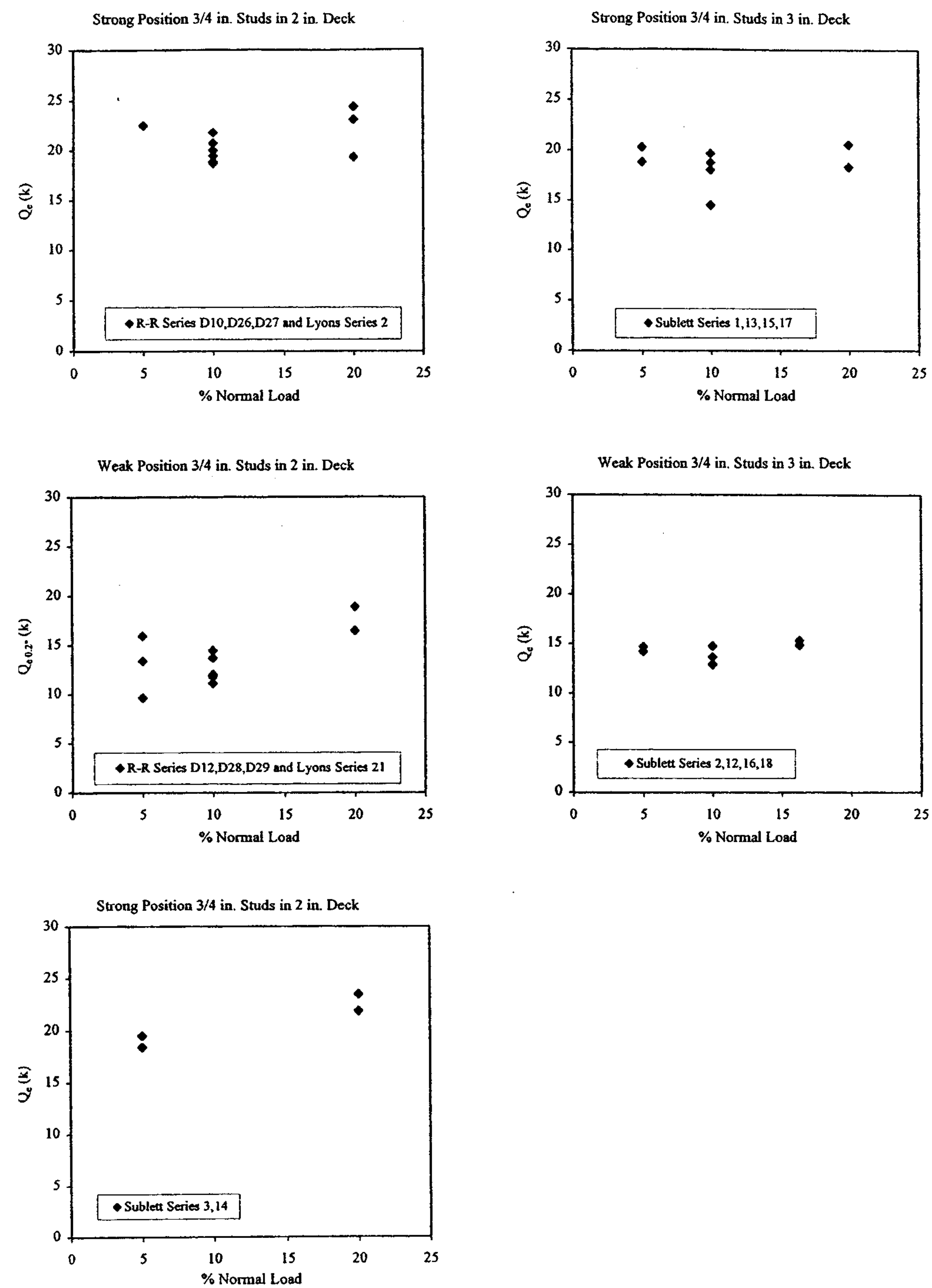

Fig. 6.14 Experimental Stud Strength vs. % Normal Load

Table 6.20 Effect of Normal Load on Elastic Stiffness of Studs

	Program	Series	Test	Total Load [T.L.] (k)	Slip* (in.)	T.L./Slip (k/in.)	Ave. T.L./Slip (k/in.)	Normal Load (%)
Strong Studs	Rambo-Roddenberry	D26	D77	19.35	0.0058	3336	3336	5
	Rambo-Roddenberry	D10	D28	40.45	0.0026	15558	8932	10
	Rambo-Roddenberry	D10	D29	20.35	0.0029	7017		
	Rambo-Roddenberry	D10	D30	25.75	0.0061	4221		
	Rambo-Roddenberry	D27	D79	43.47	0.0001	434700	161629	20
	Rambo-Roddenberry	D27	D80	42.71	0.0040	10678		
	Rambo-Roddenberry	D27	D81	39.51	0.0010	39510		
	Sublett	1	1A	25.00	0.0078	3205	3165	5
	Sublett	1	1B	25.00	0.0080	3125		
	Sublett	13	13A	30.00	0.0078	3846	6271	20
	Sublett	13	13B	20.00	0.0023	8696		
	Sublett	3	3A	40.00	0.0193	2073	1839	5
	Sublett	3	3B	35.00	0.0218	1606		
	Sublett	14	14A	30.00	0.0020	15000	8727	20
	Sublett	14	14B	40.00	0.0163	2454		
Weak Studs	Rambo-Roddenberry	D28	D82	17.84	0.0526	339	3405	5
	Rambo-Roddenberry	D28	D83	24.43	0.0036	6786		
	Rambo-Roddenberry	D28	D84	15.14	0.0049	3090		
	Rambo-Roddenberry	D12	D34	19.97	0.0076	2628	3545	10
	Rambo-Roddenberry	D12	D35	19.97	0.0061	3274		
	Rambo-Roddenberry	D12	D36	20.35	0.0043	4733		
	Rambo-Roddenberry	D29	D85	24.62	0.0023	10704	10412	20
	Rambo-Roddenberry	D29	D86	24.12	0.0032	7538		
	Rambo-Roddenberry	D29	D87	24.69	0.0019	12995		
	Sublett	2	2A	25.00	0.0163	1534	2156	5
	Sublett	2	2B	17.50	0.0063	2778		
	Sublett	12	12A	15.00	0.0038	3947	4117	10
	Sublett	12	12B	15.00	0.0035	4286		
	Sublett	16	16A	15.00	0.0018	8333	5833	16.3
	Sublett	16	16B	10.00	0.0030	3333		

* Average of all slip readings

among some of the series that were compared. The stiffnesses do not appear to be readily predictable, however the comparison shows that the elastic stiffnesses do not vary much for normal loads below 10%. When a 20% normal load is used, the specimens exhibit much larger stiffnesses.

6.10 Reduction Factor for d/t > 2.7

Tests were done by Sublett et al (1992) and Diaz et al (1998) to determine the effect of the ratio of the stud diameter-to-flange thickness, *d/t*, on stud strength. For *d/t* ≤ 2.7, as discovered by Goble (1968), there is no effect on the stud strength or failure mode. For *d/t* > 2.7, however, the studs begin to pull out of the steel flange. All of the tests discussed as part of the development of strength prediction models had *d/t* ≤ 2.7. If *d/t* > 2.7, a reduction in stud strength needs to be made.

Sublett et al (1992) did eight push-out tests on 3/4 in. x 3 1/2 in. strong position studs in 2 in. deck on several different thicknesses of base members to determine the effect of *d/t* on stud strength. These tests are summarized in Table 6.21. Sublett noticed visible angle rotation in the vicinity of the stud when *d/t* ≥ 3.0. This contributed to lower stud strengths.

Table 6.21 Effect of d/t on Stud Strength (Sublett et al 1992)

Program	Series	Test	Base Thickness (in.)	d/t	Q_e (k)	$Q_{e\ ave.}$ (k)
Sublett	3	3A	0.313	2.40	19.47	18.94
Sublett	3	3B	0.313	2.40	18.4	
Sublett	9	9A	0.25	3.00	18.54	18.67
Sublett	9	9B	0.25	3.00	18.8	
Sublett	10	10A	0.219	3.42	17.11	17.85
Sublett	10	10B	0.219	3.42	18.59	
Sublett	11	11A	0.188	3.99	16.55	16.99
Sublett	11	11B	0.188	3.99	17.43	

Series 3 had $d/t \leq 2.7$, while Series 9-11 had $d/t > 2.7$. The experimental strengths from Series 9-11 were plotted with the strengths from Series 3 in Fig. 6.15. An

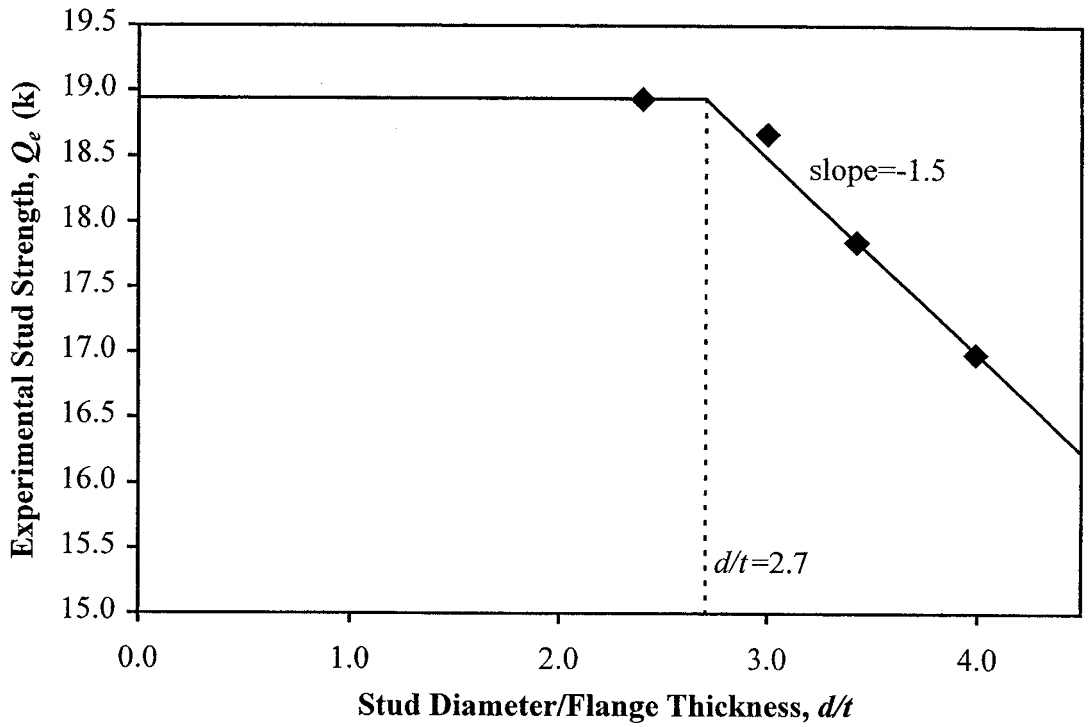

Fig. 6.15 Experimental Stud Strength vs. *d/t*

approximate linear relationship between Q_e and d/t, for $d/t > 2.7$, can be seen from this figure. This line has a slope of –1.5 k-in./in., so the stud strength decreases about 1.5 k for every 1.0 in./in. increment in d/t above 2.7. An adjustment can be made for the strength of studs with $d/t > 2.7$ by the following formula:

$$Q_{d/t>2.7} = Q_{d/t\leq 2.7} - 1.5\left(\frac{d}{t} - 2.7\right) \tag{6.16}$$

where $Q_{d/t\leq 2.7}$ is found from any of the equations developed so far for Q_{1S}, Q_{1W}, Q_{1M}, Q_{2S}, Q_{2M}, or Q_{Stag}, whichever is applicable. This formula was tested using the data from Diaz et al (1998), who performed tests on different diameter studs in 1 in. deck. The results in Table 6.22 show that the stud strength increases with decreasing *d/t*. For example,

Table 6.22 Effect of d/t on Stud Strength (Diaz 1998)

Program	Series	Test	Base Thickness (in.)	Stud Dia. (in.)	d/t	Q_e (k)	$Q_{e\ ave.}$ (k)	$Q_{d/t>2.7}$* (k)
Diaz	T1	T1-1	0.123	0.375	3.05	3.49	3.64	3.33
Diaz	T1	T1-2	0.123	0.375	3.05	3.56		
Diaz	T1	T1-3	0.123	0.375	3.05	3.87		
Diaz	T2	T2-1	0.155	0.375	2.42	3.83	3.85	--
Diaz	T2	T2-2	0.155	0.375	2.42	3.78		
Diaz	T2	T2-3	0.155	0.375	2.42	3.93		
Diaz	T4	T4-1	0.17	0.500	2.94	6.67	6.47	6.54
Diaz	T4	T4-2	0.17	0.500	2.94	6.78		
Diaz	T4	T4-3	0.17	0.500	2.94	5.97		
Diaz	T5	T5-1	0.205	0.500	2.44	7.09	6.90	--
Diaz	T5	T5-2	0.205	0.500	2.44	7.18		
Diaz	T5	T5-3	0.205	0.500	2.44	6.44		
Diaz	T7	T7-1	0.205	0.625	3.05	9.62	9.37	9.47
Diaz	T7	T7-2	0.205	0.625	3.05	9.39		
Diaz	T7	T7-3	0.205	0.625	3.05	9.11		
Diaz	T8	T8-1	0.25	0.625	2.50	10.25	9.99	--
Diaz	T8	T8-2	0.25	0.625	2.50	9.46		
Diaz	T8	T8-3	0.25	0.625	2.50	10.25		

* Stud strength predicted by Eqn. (6.16)

comparing Series T4 with Series T5 shows an increase in stud strength from 6.47 k to 6.90 k with a decrease in *d/t* from 2.94 to 2.44. Using Eqn. 6.16 and $Q_{e\ ave.}$ from Series T5 to predict the stud strength from Series T4 gives a strength of 6.54 k, which is close to the experimental strength of 6.47 k.

6.11 Friction in Composite Slabs

The effect of friction on the strength of studs in solid slabs was discussed in Sections 3.3.2 and 3.3.3. It was found that friction increases the strength of a stud in a solid slab. It has been hypothesized by Lyons et al (1994), that the strength of studs in composite slabs is also affected by friction. Fig. 6.16 is a diagram showing the forces that occur in a solid slab and in a composite slab. The shear strength of the connection, or *apparent* strength, is equal to the sum of the stud shank strength Q_s and the friction strength Q_f. The movement of the shear stud is resisted by the concrete slab C; the concrete force causes a normal force N; the normal force causes a shear force S; the normal force and bending cause tension T in the stud (Lyons et al 1994).

In a solid slab, the normal force and the friction force occur near the base of the stud. In a composite slab, these forces must occur in the next deck rib. Lyons et al (1994) hypothesized that the friction force decreases in a composite slab because the distance from the stud to the normal force is increased substantially. Because the friction force decreases, the *apparent* stud strength decreases.

If studs are located in all of the ribs of a push-out specimen, the friction forces do not occur as they would if studs were located in, for example, every other rib. All of the push-out tests performed on single studs at VT had two full ribs in each slab, or specimen half, with a stud in both ribs. All of the push-out tests on pairs of studs at VT had two full ribs in each slab, with only one pair of studs occupying one of the ribs in the slab. Thus, there is no way of evaluating this hypothesis from the VT tests.

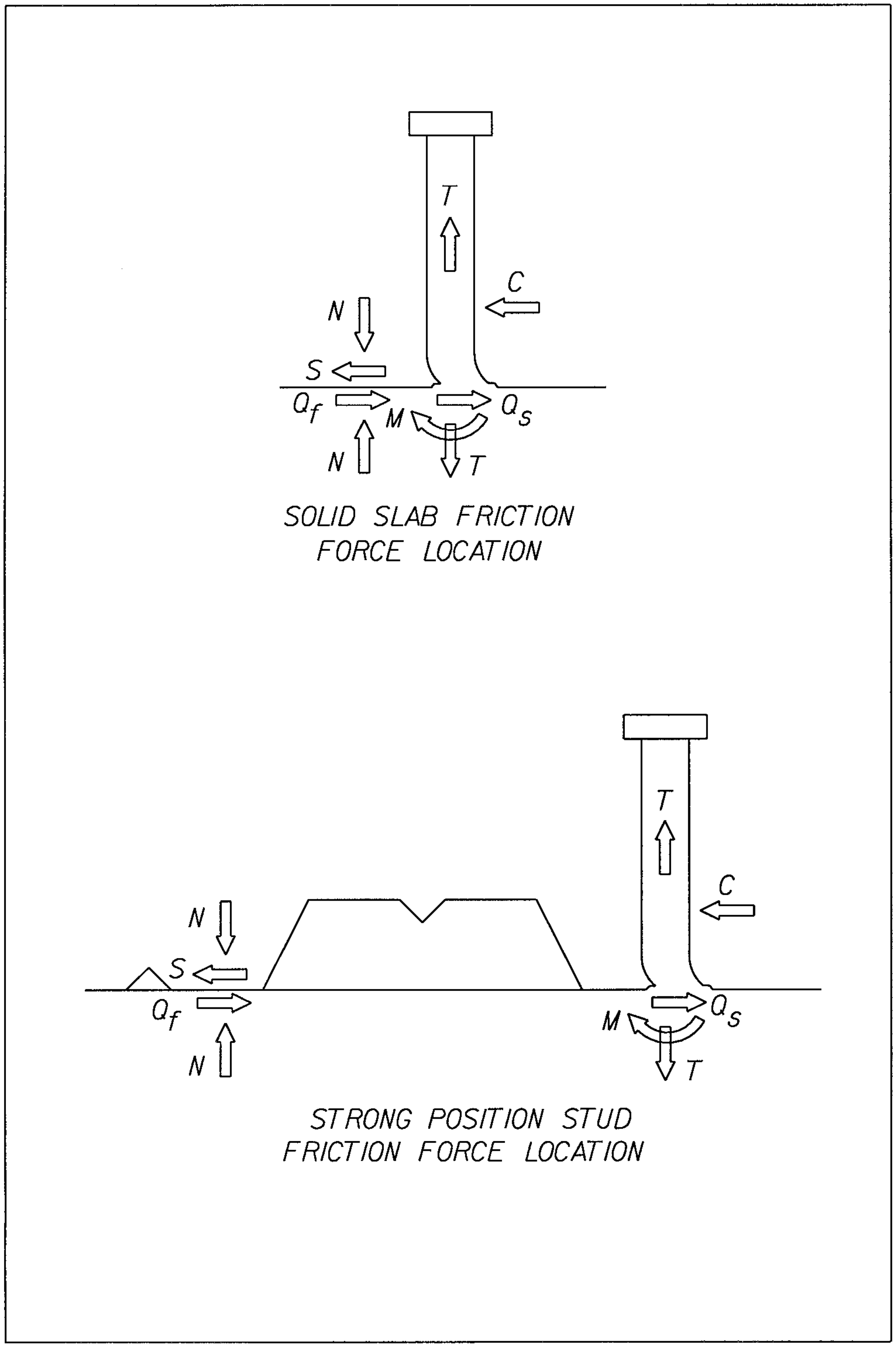

Fig. 6.16 Location of Friction Forces in a Solid Slab and a Composite Slab (after Lyons et al 1994)

Jayas and Hosain (1988), however, performed push-out tests in which the number of ribs occupied by studs was varied. The authors were investigating the effect of longitudinal stud spacing on stud strength. Pairs of 5/8 in. x 3 in. studs placed centrally in 1 1/2 in. deck, with three ribs (average rib width of 2.4 in.) per slab, were tested. In specimens where studs were placed in all three ribs in each slab, for a spacing of 6 in., the stud strength was 8.41 k. Placing studs in two of the three ribs, for a spacing of 12 in., the stud strength increased by 0.83 k, giving a strength of 9.24 k. Placing studs in only one of the three ribs increased the stud strength by another 0.83 k, giving a strength of 10.07 k.

The same pattern occurred for tests with pairs of 5/8 in. x 3 in. studs in inverted 1 1/2 in. deck (average rib width of 3.6 in.). For specimens with studs in all three ribs, the stud strength was 12.1 k. For studs in two of the three ribs, the strength increased 1.1 k, giving a strength of 13.2 k. Placing studs in only one of the three ribs increased the stud strength by another 1.0 k, giving a strength of 14.2 k.

Jayas and Hosain (1988) concluded that there is no effect of longitudinal spacing on stud strength. However, there *was* a small increase in strength. This may be due to less cracking due to the increase in spacing, or it may be due to the friction being distributed differently when studs are placed in adjacent ribs. When studs are only placed in one of the three ribs, the friction force is allowed to occur in the two ribs without studs, resulting in a larger *apparent* stud strength. When studs are placed in two of the three ribs, the friction force from the studs in both ribs is allowed to occur in only one rib (the rib without studs), resulting in a decrease in strength from the previous case.

When studs are placed in all ribs, the friction force cannot occur in the same manner because all ribs are filled with studs; this results in a further decrease in strength.

6.12 Summary of the Evaluation of Push-Out Test Results

In summary, the major parameter affecting stud strength is the position of the stud in the deck rib. The more concrete between the stud and rib, on the load-bearing side of the stud, the greater the stud strength. The stud strength is also based on its tensile strength, A_sF_u. For single studs in the strong position, which is where $e_{mid\text{-}ht.} \geq 2.2$ in., the stud strength is approximately $0.68A_sF_u$. For single studs in the weak position, which is where $e_{mid\text{-}ht.} < 2.2$ in., the stud strength is approximately $0.48A_sF_u$. For studs in the staggered position, where one stud is in the strong position and one stud in the weak position in the same rib, the strength is approximately $0.52A_sF_u$. A reduction factor of 0.85 may be applied to the equations for single strong and weak position studs for strong or weak position studs placed in pairs. Another modification may be applied on the strength of the weak position studs when decks other than 20 gauge are used. A reduction in strength is called for when $d/t \geq 2.7$.

In Table 5.1, bare stud tests showed that the strength of a stud should not exceed about $0.72A_sF_u$. For strong position studs, the stud strength from push-out tests is approximately $0.68A_sF_u$, as discussed above. This equates to a moment arm from bare stud tests of 0.07 in. from Fig. 5.4. For weak position studs, the stud strength is approximately $0.48A_sF_u$, which equates to a moment arm from bare stud tests of 0.6 in. For studs in 4 1/2 in. deck, the stud strength is approximately $0.28A_sF_u$, as reported in

Section 3.4.4. This equates to a moment arm from bare stud tests of 1.2 in. For studs in 6 in. deck, the stud strength is approximately $0.21A_sF_u$, which equates to a moment arm from bare stud tests of 1.4 in. Comparing the push-out test results to the bare stud tests demonstrates that the force in the slab that is resisted by the stud occurs very close to the base for strong position studs. This force moves away from the base for weak position studs, increasing with deeper decks.

6.13 New Strength Prediction Model

The new strength prediction model, based on the strength prediction equations developed in previous sections, is summarized as follows.

For studs in 2 in. and 3 in. deck with *d/t* ≤ 2.7,

$$Q_{sc} = R_pR_nR_dA_sF_u \quad (6.17)$$

R_p = 0.68 for $e_{mid\text{-}ht.} \geq 2.2$" (strong position studs)

= 0.48 for $e_{mid\text{-}ht.} < 2.2$" (weak position studs)

= 0.52 for staggered position studs

R_n = 1.0 for one stud per rib or staggered position studs

= 0.85 for two studs per rib

R_d = 1.0 for all strong position studs

= 0.88 for 22 gauge deck (weak studs)

= 1.0 for 20 gauge deck (weak studs)

= 1.05 for 18 gauge deck (weak studs)

= 1.11 for 16 gauge deck (weak studs)

For studs in 1 in. and 1 1/2 in. deck with *d/t* ≤ 2.7,

$$Q_{sc} = R_n 3.08 e^{0.048 A_s F_u} \tag{6.18}$$

R_n = 1.0 for one stud per rib

= 0.85 for two studs per rib

For studs in 2 in. and 3 in. deck with *d/t* > 2.7,

$$Q_{sc} = R_p R_n R_d A_s F_u - 1.5\left(\frac{d}{t} - 2.7\right) \tag{6.19}$$

For studs in 1 in. and 1 1/2 in. deck with *d/t* > 2.7,

$$Q_{sc} = R_n 3.08 e^{0.048 A_s F_u} - 1.5\left(\frac{d}{t} - 2.7\right) \tag{6.20}$$

6.14 VT Experimental and New Predicted Strengths

A final check of the model presented in Section 6.13 was performed using all push-out tests from VT, except for the tests on 7/8 in. diameter studs, with the results shown in Table 6.23 and plotted in Fig. 6.17. The statistics were calculated as follows.

R = 0.919

Average ratio Q_e/Q_{sc} = 1.027

Minimum ratio Q_e/Q_{sc} = 0.671

Maximum ratio Q_e/Q_{sc} = 1.638

Coefficient of variation = 15.5%

6.15 VT Strength Model Compared with Published Data

Push-out test results from Jayas and Hosain (1988), Lloyd and Wright (1990), Mottram and Johnson (1990), Robinson (1988) and Johnson and Yuan (1997) are compared with predicted strengths from the model presented in Section 6.13. The results, the statistics for which are given below, are shown in Table 6.24 and plotted in Fig. 6.18.

R = 0.725

Average ratio Q_e/Q_{sc} = 1.073

Minimum ratio Q_e/Q_{sc} = 0.624

Maximum ratio Q_e/Q_{sc} = 1.711

Coefficient of variation = 18.4%

Table 6.23 VT Experimental Strengths and New Predicted Strengths

Program	Series	Test	Stud Layout	Q_e (k)	d/t	R_p	R_n	R_d	A_sF_u (k)	Q_{sc} (k)	Q_e/Q_{sc}	$Q_{e\ ave.}$ (k)	$Q_{e\ ave.}/Q_{sc}$
Rambo-Roddenberry	D1	D1	S	9.77	0.96	0.68	1.00	1.00	14.54	9.89	0.988	8.76	0.886
Rambo-Roddenberry	D1	D2	S	7.29	0.96	0.68	1.00	1.00	14.54	9.89	0.737		
Rambo-Roddenberry	D1	D3	S	9.23	0.96	0.68	1.00	1.00	14.54	9.89	0.934		
Rambo-Roddenberry	D2	D4	2S	8.95	0.96	0.68	0.85	1.00	14.54	8.40	1.065	8.29	0.986
Rambo-Roddenberry	D2	D5	2S	8.76	0.96	0.68	0.85	1.00	14.54	8.40	1.042		
Rambo-Roddenberry	D2	D6	2S	7.16	0.96	0.68	0.85	1.00	14.54	8.40	0.852		
Rambo-Roddenberry	D3	D7	W	5.81	0.96	0.48	1.00	1.00	14.54	6.98	0.833	6.69	0.959
Rambo-Roddenberry	D3	D8	W	7.44	0.96	0.48	1.00	1.00	14.54	6.98	1.066		
Rambo-Roddenberry	D3	D9	W	6.82	0.96	0.48	1.00	1.00	14.54	6.98	0.977		
Rambo-Roddenberry	D4	D10	S	12.53	1.20	0.68	1.00	1.00	22.28	15.15	0.827	13.87	0.916
Rambo-Roddenberry	D4	D11	S	13.54	1.20	0.68	1.00	1.00	22.28	15.15	0.894		
Rambo-Roddenberry	D4	D12	S	15.55	1.20	0.68	1.00	1.00	22.28	15.15	1.026		
Rambo-Roddenberry	D5	D13	W	11.81	1.20	0.48	1.00	1.00	20.56	9.87	1.197	10.45	1.059
Rambo-Roddenberry	D5	D14	W	9.99	1.20	0.48	1.00	1.00	20.56	9.87	1.012		
Rambo-Roddenberry	D5	D15	W	9.55	1.20	0.48	1.00	1.00	20.56	9.87	0.968		
Rambo-Roddenberry	D6	D16	2S	11.87	1.20	0.68	0.85	1.00	22.28	12.88	0.922	13.65	1.059
Rambo-Roddenberry	D6	D17	2S	15.42	1.20	0.68	0.85	1.00	22.28	12.88	1.197		
Rambo-Roddenberry	D7	D19	S	8.86	0.96	0.68	1.00	1.00	14.54	9.89	0.896	8.21	0.830
Rambo-Roddenberry	D7	D20	S	9.14	0.96	0.68	1.00	1.00	14.54	9.89	0.924		
Rambo-Roddenberry	D7	D21	S	6.63	0.96	0.68	1.00	1.00	14.54	9.89	0.671		
Rambo-Roddenberry	D8	D22	2S	9.23	0.96	0.68	0.85	1.00	14.54	8.40	1.098	10.33	1.229
Rambo-Roddenberry	D8	D23	2S	10.30	0.96	0.68	0.85	1.00	14.54	8.40	1.226		
Rambo-Roddenberry	D8	D24	2S	11.46	0.96	0.68	0.85	1.00	14.54	8.40	1.364		
Rambo-Roddenberry	D9	D25	W	7.85	0.96	0.48	1.00	1.00	14.54	6.98	1.125	7.35	1.053
Rambo-Roddenberry	D9	D26	W	7.32	0.96	0.48	1.00	1.00	14.54	6.98	1.049		
Rambo-Roddenberry	D9	D27	W	6.88	0.96	0.48	1.00	1.00	14.54	6.98	0.986		
Rambo-Roddenberry	D10	D28	S	20.01	1.44	0.68	1.00	1.00	29.08	19.77	1.012	20.18	1.021
Rambo-Roddenberry	D10	D29	S	18.72	1.44	0.68	1.00	1.00	29.08	19.77	0.947		
Rambo-Roddenberry	D10	D30	S	21.80	1.44	0.68	1.00	1.00	29.08	19.77	1.103		
Rambo-Roddenberry	D11	D32	2S	17.49	1.44	0.68	0.85	1.00	29.08	16.81	1.041	19.19	1.142

Table 6.23 VT Experimental Strengths and New Predicted Strengths (cont'd.)

Program	Series	Test	Stud Layout	Q_e (k)	d/t	R_p	R_n	R_d	A_sF_u (k)	Q_{sc} (k)	Q_e/Q_{sc}	$Q_{e\ ave.}$ (k)	$Q_{e\ ave.}/Q_{sc}$
Rambo-Roddenberry	D11	D33	2S	20.89	1.44	0.68	0.85	1.00	29.08	16.81	1.243		
Rambo-Roddenberry	D12	D34	W	11.81	1.44	0.48	1.00	1.00	29.08	13.96	0.846	12.74	0.913
Rambo-Roddenberry	D12	D35	W	12.00	1.44	0.48	1.00	1.00	29.08	13.96	0.860		
Rambo-Roddenberry	D12	D36	W	14.42	1.44	0.48	1.00	1.00	29.08	13.96	1.033		
Rambo-Roddenberry	D13	D37	S	16.18	1.20	0.68	1.00	1.00	22.28	15.15	1.068	15.93	1.051
Rambo-Roddenberry	D13	D38	S	17.07	1.20	0.68	1.00	1.00	22.28	15.15	1.126		
Rambo-Roddenberry	D13	D39	S	14.53	1.20	0.68	1.00	1.00	22.28	15.15	0.959		
Rambo-Roddenberry	D14	D40	2S	14.70	1.20	0.68	0.85	1.00	22.28	12.88	1.141	16.36	1.270
Rambo-Roddenberry	D14	D41	2S	16.95	1.20	0.68	0.85	1.00	22.28	12.88	1.316		
Rambo-Roddenberry	D14	D42	2S	17.43	1.20	0.68	0.85	1.00	22.28	12.88	1.353		
Rambo-Roddenberry	D15	D43	W	8.78	1.20	0.48	1.00	1.00	22.28	10.70	0.821	9.45	0.883
Rambo-Roddenberry	D15	D44	W	9.64	1.20	0.48	1.00	1.00	22.28	10.70	0.901		
Rambo-Roddenberry	D15	D45	W	9.93	1.20	0.48	1.00	1.00	22.28	10.70	0.928		
Rambo-Roddenberry	D16	D46	S	5.89	0.72	0.68	1.00	1.00	8.75	5.95	0.990	5.48	0.921
Rambo-Roddenberry	D16	D47	S	5.18	0.72	0.68	1.00	1.00	8.75	5.95	0.871		
Rambo-Roddenberry	D16	D48	S	5.36	0.72	0.68	1.00	1.00	8.75	5.95	0.901		
Rambo-Roddenberry	D18	D52	W	4.05	0.72	0.48	1.00	1.00	8.75	4.20	0.965	4.47	1.064
Rambo-Roddenberry	D18	D53	W	4.54	0.72	0.48	1.00	1.00	8.75	4.20	1.081		
Rambo-Roddenberry	D18	D54	W	4.81	0.72	0.48	1.00	1.00	8.75	4.20	1.146		
Rambo-Roddenberry	D20	D58	S	6.03	0.72	0.68	1.00	1.00	8.53	5.80	1.039	7.88	1.358
Rambo-Roddenberry	D20	D59	S	8.10	0.72	0.68	1.00	1.00	8.53	5.80	1.396		
Rambo-Roddenberry	D20	D60	S	9.50	0.72	0.68	1.00	1.00	8.53	5.80	1.638		
Rambo-Roddenberry	D22	D64	W	5.40	0.72	0.48	1.00	1.00	8.53	4.09	1.319	6.18	1.509
Rambo-Roddenberry	D22	D65	W	6.68	0.72	0.48	1.00	1.00	8.53	4.09	1.631		
Rambo-Roddenberry	D22	D66	W	6.46	0.72	0.48	1.00	1.00	8.53	4.09	1.578		
Lyons	1	D2	S	21.91	1.44	0.68	1.00	0.88	29.41	17.60	1.245	20.00	1.136
Lyons	1	D3	S	18.08	1.44	0.68	1.00	0.88	29.41	17.60	1.027		
Lyons	2	D4	S	19.44	1.44	0.68	1.00	0.88	29.41	17.60	1.105	19.67	1.118
Lyons	2	D5	S	18.85	1.44	0.68	1.00	0.88	29.41	17.60	1.071		
Lyons	2	D6	S	20.73	1.44	0.68	1.00	0.88	29.41	17.60	1.178		

Table 6.23 VT Experimental Strengths and New Predicted Strengths (cont'd.)

Program	Series	Test	Stud Layout	Q_e (k)	d/t	R_p	R_n	R_d	A_sF_u (k)	Q_{sc} (k)	Q_e/Q_{sc}	$Q_{e\ ave.}$ (k)	$Q_{e\ ave.}/Q_{sc}$
Lyons	3	D7	S	21.18	1.44	0.68	1.00	0.88	29.41	17.60	1.204	21.00	1.194
Lyons	3	D8	S	20.37	1.44	0.68	1.00	0.88	29.41	17.60	1.158		
Lyons	3	D9	S	21.46	1.44	0.68	1.00	0.88	29.41	17.60	1.220		
Lyons	4	D10	S	20.62	1.44	0.68	1.00	0.88	28.74	17.20	1.199	21.20	1.233
Lyons	4	D11	S	21.02	1.44	0.68	1.00	0.88	28.74	17.20	1.222		
Lyons	4	D12	S	21.97	1.44	0.68	1.00	0.88	28.74	17.20	1.278		
Lyons	5	D13	S	19.84	1.44	0.68	1.00	0.88	28.69	17.17	1.156	20.48	1.193
Lyons	5	D14	S	20.14	1.44	0.68	1.00	0.88	28.69	17.17	1.173		
Lyons	5	D15	S	21.45	1.44	0.68	1.00	0.88	28.69	17.17	1.250		
Lyons	6	D52	S	17.39	1.44	0.68	1.00	1.00	29.41	20.00	0.870	16.78	0.839
Lyons	6	D53	S	14.61	1.44	0.68	1.00	1.00	29.41	20.00	0.731		
Lyons	6	D54	S	18.35	1.44	0.68	1.00	1.00	29.41	20.00	0.918		
Lyons	7	D55	S	18.21	1.44	0.68	1.00	1.00	28.74	19.54	0.932	17.33	0.887
Lyons	7	D56	S	15.49	1.44	0.68	1.00	1.00	28.74	19.54	0.793		
Lyons	7	D57	S	18.30	1.44	0.68	1.00	1.00	28.74	19.54	0.936		
Lyons	8	D58	S	18.67	1.44	0.68	1.00	1.00	28.69	19.51	0.957	18.57	0.952
Lyons	8	D59	S	19.60	1.44	0.68	1.00	1.00	28.69	19.51	1.005		
Lyons	8	D60	S	17.45	1.44	0.68	1.00	1.00	28.69	19.51	0.895		
Lyons	9	D16	STAG	11.48	1.44	0.52	1.00	0.88	29.41	13.46	0.853	12.59	0.936
Lyons	9	D17	STAG	14.22	1.44	0.52	1.00	0.88	29.41	13.46	1.057		
Lyons	9	D18	STAG	12.08	1.44	0.52	1.00	0.88	29.41	13.46	0.898		
Lyons	10	D19	STAG	15.49	1.44	0.52	1.00	0.88	29.41	13.46	1.151	15.29	1.137
Lyons	10	D20	STAG	15.28	1.44	0.52	1.00	0.88	29.41	13.46	1.136		
Lyons	10	D21	STAG	15.11	1.44	0.52	1.00	0.88	29.41	13.46	1.123		
Lyons	11	D22	STAG	12.91	1.44	0.52	1.00	0.88	29.41	13.46	0.959	14.16	1.052
Lyons	11	D23	STAG	15.35	1.44	0.52	1.00	0.88	29.41	13.46	1.141		
Lyons	11	D24	STAG	14.21	1.44	0.52	1.00	0.88	29.41	13.46	1.056		
Lyons	12	D25	STAG	11.47	1.44	0.52	1.00	0.88	28.74	13.15	0.872	13.55	1.030
Lyons	12	D26	STAG	15.08	1.44	0.52	1.00	0.88	28.74	13.15	1.147		
Lyons	12	D27	STAG	14.10	1.44	0.52	1.00	0.88	28.74	13.15	1.072		

Table 6.23 VT Experimental Strengths and New Predicted Strengths (cont'd.)

Program	Series	Test	Stud Layout	Q_e (k)	d/t	R_p	R_n	R_d	A_sF_u (k)	Q_{sc} (k)	Q_e/Q_{sc}	$Q_{e\ ave.}$ (k)	$Q_{e\ ave.}/Q_{sc}$
Lyons	13	D76	STAG	13.34	1.44	0.52	1.00	1.00	29.77	15.48	0.862	14.26	0.921
Lyons	13	D77	STAG	14.95	1.44	0.52	1.00	1.00	29.77	15.48	0.966		
Lyons	13	D78	STAG	14.50	1.44	0.52	1.00	1.00	29.77	15.48	0.937		
Lyons	14	D64	STAG	13.70	1.44	0.52	1.00	1.00	28.74	14.94	0.917	13.44	0.900
Lyons	14	D65	STAG	14.12	1.44	0.52	1.00	1.00	28.74	14.94	0.945		
Lyons	14	D66	STAG	12.51	1.44	0.52	1.00	1.00	28.74	14.94	0.837		
Lyons	15	D67	STAG	14.02	1.44	0.52	1.00	1.00	28.69	14.92	0.940	14.64	0.981
Lyons	15	D68	STAG	14.96	1.44	0.52	1.00	1.00	28.69	14.92	1.003		
Lyons	15	D69	STAG	14.94	1.44	0.52	1.00	1.00	28.69	14.92	1.002		
Lyons	16	D28	2S	15.50	1.44	0.68	0.85	0.88	29.41	14.96	1.036	15.71	1.051
Lyons	16	D29	2S	15.59	1.44	0.68	0.85	0.88	29.41	14.96	1.042		
Lyons	16	D30	2S	16.05	1.44	0.68	0.85	0.88	29.41	14.96	1.073		
Lyons	17	D31	2S	12.37	1.44	0.68	0.85	0.88	29.41	14.96	0.827	15.04	1.006
Lyons	17	D32	2S	14.46	1.44	0.68	0.85	0.88	29.41	14.96	0.967		
Lyons	17	D33	2S	18.30	1.44	0.68	0.85	0.88	29.41	14.96	1.223		
Lyons	18	D34	2S	17.86	1.44	0.68	0.85	0.88	29.41	14.96	1.194	16.95	1.133
Lyons	18	D35	2S	16.10	1.44	0.68	0.85	0.88	29.41	14.96	1.076		
Lyons	18	D36	2S	16.89	1.44	0.68	0.85	0.88	29.41	14.96	1.129		
Lyons	19	D37	2S	16.52	1.44	0.68	0.85	0.88	28.74	14.62	1.130	16.24	1.111
Lyons	19	D38	2S	17.76	1.44	0.68	0.85	0.88	28.74	14.62	1.215		
Lyons	19	D39	2S	14.43	1.44	0.68	0.85	0.88	28.74	14.62	0.987		
Lyons	20	D40	W	10.95	1.44	0.48	1.00	0.88	29.41	12.42	0.882	10.73	0.864
Lyons	20	D41	W	10.96	1.44	0.48	1.00	0.88	29.41	12.42	0.882		
Lyons	20	D42	W	10.29	1.44	0.48	1.00	0.88	29.41	12.42	0.828		
Lyons	21	D43	W	11.09	1.44	0.48	1.00	1.00	29.41	14.12	0.786	12.17	0.862
Lyons	21	D44	W	11.75	1.44	0.48	1.00	1.00	29.41	14.12	0.832		
Lyons	21	D45	W	13.66	1.44	0.48	1.00	1.00	29.41	14.12	0.968		
Lyons	22	D46	W	10.67	1.44	0.48	1.00	1.05	29.41	14.82	0.720	12.74	0.860
Lyons	22	D47	W	14.19	1.44	0.48	1.00	1.05	29.41	14.82	0.957		
Lyons	22	D48	W	13.36	1.44	0.48	1.00	1.05	29.41	14.82	0.901		

Table 6.23 VT Experimental Strengths and New Predicted Strengths (cont'd.)

Program	Series	Test	Stud Layout	Q_e (k)	d/t	R_p	R_n	R_d	A_sF_u (k)	Q_{sc} (k)	Q_e/Q_{sc}	$Q_{e\ ave.}$ (k)	$Q_{e\ ave.}/Q_{sc}$
Lyons	23	D49	W	15.02	1.44	0.48	1.00	1.11	29.41	15.67	0.959	13.48	0.860
Lyons	23	D50	W	11.71	1.44	0.48	1.00	1.11	29.41	15.67	0.747		
Lyons	23	D51	W	13.70	1.44	0.48	1.00	1.11	29.41	15.67	0.874		
Lyons	24	D61	STAG	14.13	1.44	0.52	1.00	0.88	29.41	13.46	1.050	14.75	1.096
Lyons	24	D62	STAG	15.32	1.44	0.52	1.00	0.88	29.41	13.46	1.138		
Lyons	24	D63	STAG	14.81	1.44	0.52	1.00	0.88	29.41	13.46	1.101		
Lyons	25	D79	STAG	16.13	1.44	0.52	1.00	0.88	29.77	13.62	1.184	16.24	1.193
Lyons	25	D80	STAG	15.50	1.44	0.52	1.00	0.88	29.77	13.62	1.138		
Lyons	25	D81	STAG	17.10	1.44	0.52	1.00	0.88	29.77	13.62	1.255		
Lyons	26	D70	STAG	14.01	1.44	0.52	1.00	0.88	28.74	13.15	1.065	14.26	1.084
Lyons	26	D71	STAG	15.21	1.44	0.52	1.00	0.88	28.74	13.15	1.157		
Lyons	26	D72	STAG	13.56	1.44	0.52	1.00	0.88	28.74	13.15	1.031		
Lyons	27	D73	2S	15.79	1.44	0.68	0.85	0.88	29.41	14.96	1.056	15.46	1.034
Lyons	27	D74	2S	14.99	1.44	0.68	0.85	0.88	29.41	14.96	1.002		
Lyons	27	D75	2S	15.61	1.44	0.68	0.85	0.88	29.41	14.96	1.044		
Lyons	28	D82	2S	16.92	1.44	0.68	0.85	0.88	28.66	14.58	1.161	17.29	1.186
Lyons	28	D83	2S	19.42	1.44	0.68	0.85	0.88	28.66	14.58	1.332		
Lyons	28	D84	2S	15.53	1.44	0.68	0.85	0.88	28.66	14.58	1.065		
Lyons	29	D85	2S	18.88	1.44	0.68	0.85	0.88	29.77	15.14	1.247	20.16	1.331
Lyons	29	D86	2S	20.92	1.44	0.68	0.85	0.88	29.77	15.14	1.382		
Lyons	29	D87	2S	20.67	1.44	0.68	0.85	0.88	29.77	15.14	1.365		
Sublett	1	1A	S	18.83	2.40	0.68	1.00	1.00	28.72	19.53	0.964	19.57	1.002
Sublett	1	1B	S	20.30	2.40	0.68	1.00	1.00	28.72	19.53	1.040		
Sublett	2	2A	W	14.20	2.40	0.48	1.00	1.00	28.72	13.78	1.030	14.45	1.048
Sublett	2	2B	W	14.70	2.40	0.48	1.00	1.00	28.72	13.78	1.066		
Sublett	3	3A	S	19.47	2.40	0.68	1.00	1.00	28.72	19.53	0.997	18.94	0.970
Sublett	3	3B	S	18.40	2.40	0.68	1.00	1.00	28.72	19.53	0.942		
Sublett	4	4A	W	13.52	2.40	0.48	1.00	1.00	28.72	13.78	0.981	13.64	0.989
Sublett	4	4B	W	13.75	2.40	0.48	1.00	1.00	28.72	13.78	0.998		
Sublett	5	5A	M	10.39	2.40		1.00	1.00	28.72	12.22	1.176	11.07	0.905

Table 6.23 VT Experimental Strengths and New Predicted Strengths (cont'd.)

Program	Series	Test	Stud Layout	Q_e (k)	d/t	R_p	R_n	R_d	A_sF_u (k)	Q_{sc} (k)	Q_e/Q_{sc}	$Q_{e\,ave.}$ (k)	$Q_{e\,ave.}/Q_{sc}$
Sublett	5	5B	M	11.74	2.40		1.00	1.00	28.72	12.22	1.041		
Sublett	8	8B	S	21.29	2.00	0.68	1.00	1.00	28.72	19.53	1.090	21.29	1.090
Sublett	9	9A	S	18.54	3.00	0.68	1.00	1.00	28.72	19.08	0.972	18.67	0.979
Sublett	9	9B	S	18.80	3.00	0.68	1.00	1.00	28.72	19.08	0.985		
Sublett	10	10A	S	17.11	3.43	0.68	1.00	1.00	28.72	18.43	0.928	17.85	0.968
Sublett	10	10B	S	18.59	3.43	0.68	1.00	1.00	28.72	18.43	1.008		
Sublett	11	11A	S	16.55	4.00	0.68	1.00	1.00	28.72	17.58	0.942	16.99	0.967
Sublett	11	11B	S	17.43	4.00	0.68	1.00	1.00	28.72	17.58	0.992		
Sublett	12	12A	W	15.31	2.40	0.48	1.00	1.00	28.72	13.78	1.111	15.08	1.094
Sublett	12	12B	W	14.85	2.40	0.48	1.00	1.00	28.72	13.78	1.077		
Sublett	13	13A	S	18.28	2.40	0.68	1.00	1.00	28.72	19.53	0.936	19.41	0.994
Sublett	13	13B	S	20.53	2.40	0.68	1.00	1.00	28.72	19.53	1.051		
Sublett	14	14A	S	23.48	2.40	0.68	1.00	1.00	28.72	19.53	1.202	22.69	1.162
Sublett	14	14B	S	21.89	2.40	0.68	1.00	1.00	28.72	19.53	1.121		
Sublett	15	15A	S	18.03	2.00	0.68	1.00	1.00	28.72	19.53	0.923	18.85	0.965
Sublett	15	15B	S	19.66	2.00	0.68	1.00	1.00	28.72	19.53	1.007		
Sublett	16	16A	W	13.66	2.00	0.48	1.00	1.00	28.72	13.78	0.991	13.25	0.961
Sublett	16	16B	W	12.84	2.00	0.48	1.00	1.00	28.72	13.78	0.932		
Sublett	17	17A	S	14.48	2.00	0.68	1.00	1.00	28.72	19.53	0.742	16.62	0.851
Sublett	17	17B	S	18.76	2.00	0.68	1.00	1.00	28.72	19.53	0.961		
Sublett	18	18A	W	12.92	2.00	0.48	1.00	1.00	28.72	13.78	0.937	13.57	0.984
Sublett	18	18B	W	14.22	2.00	0.48	1.00	1.00	28.72	13.78	1.032		
Diaz	T1	T1-1	M	3.49	3.05		1.00		5.60	3.51	1.005	3.64	1.038
Diaz	T1	T1-2	M	3.56	3.05		1.00		5.60	3.51	0.985		
Diaz	T1	T1-3	M	3.87	3.05		1.00		5.60	3.51	0.906		
Diaz	T2	T2-1	M	3.83	2.42		1.00		5.60	4.03	1.052	3.85	0.955
Diaz	T2	T2-2	M	3.78	2.42		1.00		5.60	4.03	1.066		
Diaz	T2	T2-3	M	3.93	2.42		1.00		5.60	4.03	1.025		
Diaz	T3	T3-1	2M	3.38	2.42		0.85		5.60	3.43	1.013	3.49	1.018
Diaz	T3	T3-2	2M	3.48	2.42		0.85		5.60	3.43	0.984		

Table 6.23 VT Experimental Strengths and New Predicted Strengths (cont'd.)

Program	Series	Test	Stud Layout	Q_e (k)	d/t	R_p	R_n	R_d	A_sF_u (k)	Q_{sc} (k)	Q_e/Q_{sc}	$Q_{e\ ave.}$ (k)	$Q_{e\ ave.}/Q_{sc}$
Diaz	T3	T3-3	2M	3.60	2.42		0.85		5.60	3.43	0.951		
Diaz	T4	T4-1	M	6.67	2.94		1.00		15.57	6.14	0.921	6.47	1.054
Diaz	T4	T4-2	M	6.78	2.94		1.00		15.57	6.14	0.906		
Diaz	T4	T4-3	M	5.97	2.94		1.00		15.57	6.14	1.029		
Diaz	T5	T5-1	M	7.09	2.44		1.00		15.57	6.50	0.917	6.90	1.062
Diaz	T5	T5-2	M	7.18	2.44		1.00		15.57	6.50	0.906		
Diaz	T5	T5-3	M	6.44	2.44		1.00		15.57	6.50	1.010		
Diaz	T6	T6-1	2M	5.88	2.44		0.85		15.57	5.53	0.940	5.55	1.005
Diaz	T6	T6-2	2M	5.50	2.44		0.85		15.57	5.53	1.005		
Diaz	T6	T6-3	2M	5.28	2.44		0.85		15.57	5.53	1.047		
Diaz	T7	T7-1	M	9.62	3.05		1.00		23.78	9.12	0.948	9.37	1.028
Diaz	T7	T7-2	M	9.39	3.05		1.00		23.78	9.12	0.971		
Diaz	T7	T7-3	M	9.11	3.05		1.00		23.78	9.12	1.001		
Diaz	T8	T8-1	M	10.25	2.50		1.00		23.78	9.64	0.941	9.99	1.036
Diaz	T8	T8-2	M	9.46	2.50		1.00		23.78	9.64	1.019		
Diaz	T8	T8-3	M	10.25	2.50		1.00		23.78	9.64	0.941		
Diaz	T9	T9-1	M	11.14	3.05		1.00		23.78	9.12	0.819	11.23	1.231
Diaz	T9	T9-2	M	11.18	3.05		1.00		23.78	9.12	0.816		
Diaz	T9	T9-3	M	11.36	3.05		1.00		23.78	9.12	0.803		
Diaz	T10	T10-1	M	12.21	2.50		1.00		23.78	9.64	0.790	12.22	1.267
Diaz	T10	T10-2	M	12.33	2.50		1.00		23.78	9.64	0.782		
Diaz	T10	T10-3	M	12.12	2.50		1.00		23.78	9.64	0.796		

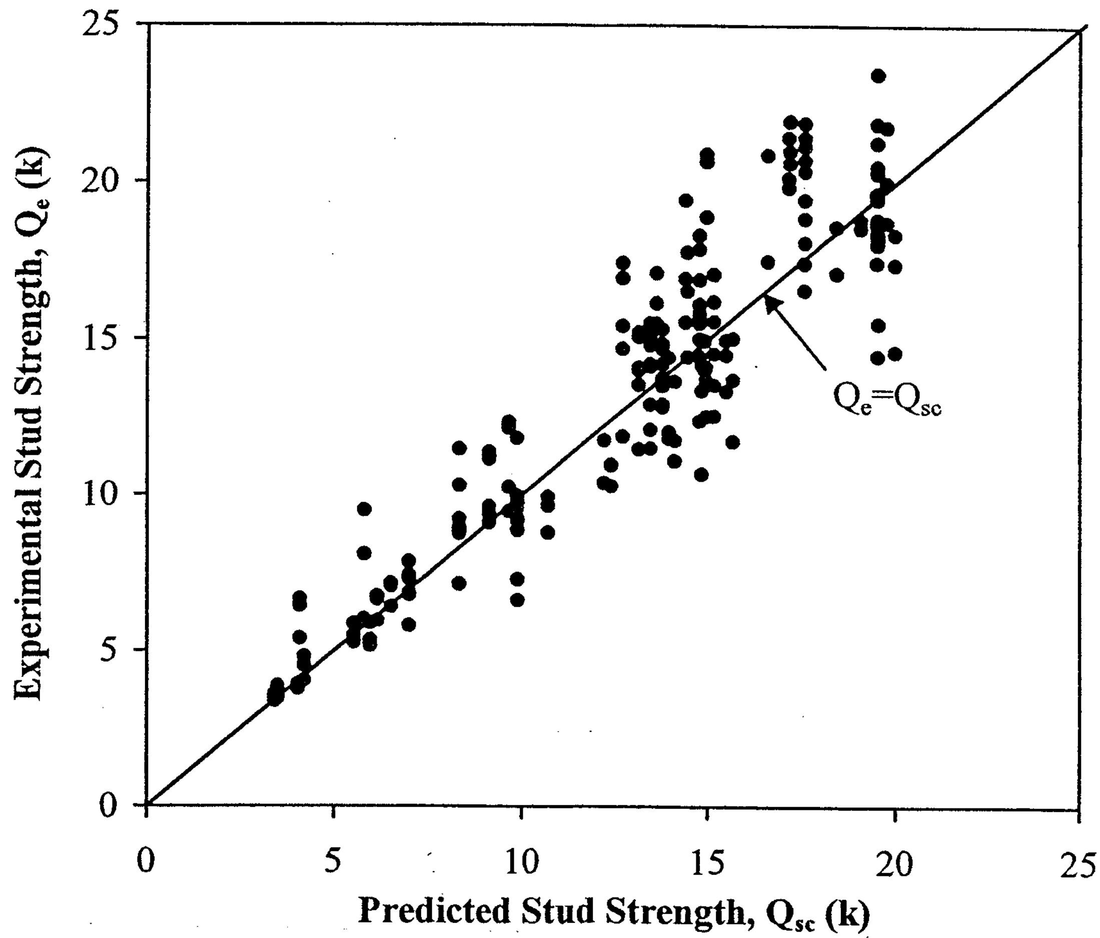

Fig. 6.17 Experimental Stud Strength vs. Predicted Stud Strength For VT Tests Using New Model

Table 6.24 VT Strength Model Compared with Published Data

Program	Series	Test	Stud Layout	Stud Diameter (in.)	Stud Height A.W. (in.)	Stud Fu (ksi)	Deck Height (in.)	Deck Gauge	Q_e (k)	R_p	R_n	R_d	A_sF_u (k)	Qsc (k)	Q_e/Qsc
Jayas and Hosain (1988)	50	1 JDT-1	2W	0.63	3	65.000 *	1.5	?	9.24	0.48	0.85	1.00	20.26	8.27	1.12
Jayas and Hosain (1988)	51	2 JDT-3	2W	0.63	3	65.000 *	1.5	?	8.40	0.48	0.85	1.00	20.26	8.27	1.02
Jayas and Hosain (1988)	52	3 JDT-5	2W	0.63	3	65.000 *	1.5	?	10.08	0.48	0.85	1.00	20.26	8.27	1.22
Jayas and Hosain (1988)	53	4 JDT-2	2W	0.63	3	65.000 *	1.5	?	13.16	0.48	0.85	1.00	20.26	8.27	1.59
Jayas and Hosain (1988)	54	5 JDT-4	2W	0.63	3	65.000 *	1.5	?	12.13	0.48	0.85	1.00	20.26	8.27	1.47
Jayas and Hosain (1988)	55	6 JDT-6	2W	0.63	3	65.000 *	1.5	?	14.15	0.48	0.85	1.00	20.26	8.27	1.71
Jayas and Hosain (1988)	56	7 JDT-7	2S	0.75	5	65.000 *	3	?	10.36	0.68	0.85	1.00	28.72	16.60	0.62
Jayas and Hosain (1988)	57	8 JDT-8	S	0.75	5	65.000 *	3	?	16.75	0.68	1.00	1.00	28.72	19.53	0.86
Lloyd &Wright (1990)	58	1A S1	S	0.75	3.94	65.000 *	2	18	21.65	0.68	1.00	1.00	28.72	19.53	1.11
Lloyd &Wright (1990)	58	1B S1	S	0.75	3.94	65.000 *	2	18	21.63	0.68	1.00	1.00	28.72	19.53	1.11
Lloyd &Wright (1990)	58	1C S1	S	0.75	3.94	65.000 *	2	18	20.97	0.68	1.00	1.00	28.72	19.53	1.07
Lloyd &Wright (1990)	59	2A S2	S	0.75	3.94	65.000 *	2	18	18.73	0.68	1.00	1.00	28.72	19.53	0.96
Lloyd &Wright (1990)	59	2B S2	S	0.75	3.94	65.000 *	2	18	18.84	0.68	1.00	1.00	28.72	19.53	0.96
Lloyd &Wright (1990)	59	2C S2	S	0.75	3.94	65.000 *	2	18	17.60	0.68	1.00	1.00	28.72	19.53	0.90
Lloyd &Wright (1990)	60	3A S3	S	0.75	3.94	65.000 *	2	18	17.80	0.68	1.00	1.00	28.72	19.53	0.91
Lloyd &Wright (1990)	60	3B S3	S	0.75	3.94	65.000 *	2	18	22.48	0.68	1.00	1.00	28.72	19.53	1.15
Lloyd &Wright (1990)	60	3C S3	S	0.75	3.94	65.000 *	2	18	20.35	0.68	1.00	1.00	28.72	19.53	1.04
Lloyd &Wright (1990)	61	4A S4	S	0.75	3.94	65.000 *	2	18	21.54	0.68	1.00	1.00	28.72	19.53	1.10
Lloyd &Wright (1990)	61	4B S4	S	0.75	3.94	65.000 *	2	18	20.62	0.68	1.00	1.00	28.72	19.53	1.06
Lloyd &Wright (1990)	61	4C S4	S	0.75	3.94	65.000 *	2	18	22.48	0.68	1.00	1.00	28.72	19.53	1.15
Lloyd &Wright (1990)	62	5A S5	S	0.75	3.94	65.000 *	2	18	22.53	0.68	1.00	1.00	28.72	19.53	1.15
Lloyd &Wright (1990)	62	5B S5	S	0.75	3.94	65.000 *	2	18	24.39	0.68	1.00	1.00	28.72	19.53	1.25
Lloyd &Wright (1990)	62	5C S5	S	0.75	3.94	65.000 *	2	18	22.48	0.68	1.00	1.00	28.72	19.53	1.15
Lloyd &Wright (1990)	63	6A S6	S	0.75	3.94	65.000 *	2	18	21.87	0.68	1.00	1.00	28.72	19.53	1.12
Lloyd &Wright (1990)	63	6B S6	S	0.75	3.94	65.000 *	2	18	22.71	0.68	1.00	1.00	28.72	19.53	1.16
Lloyd &Wright (1990)	63	6C S6	S	0.75	3.94	65.000 *	2	18	22.03	0.68	1.00	1.00	28.72	19.53	1.13
Lloyd &Wright (1990)	64	7A S7	S	0.75	3.94	65.000 *	2	18	22.59	0.68	1.00	1.00	28.72	19.53	1.16
Lloyd &Wright (1990)	64	7B S7	S	0.75	3.94	65.000 *	2	18	21.36	0.68	1.00	1.00	28.72	19.53	1.09
Lloyd &Wright (1990)	64	7C S7	S	0.75	3.94	65.000 *	2	18	20.05	0.68	1.00	1.00	28.72	19.53	1.03
Lloyd &Wright (1990)	65	8A S8	S	0.75	3.94	65.000 *	2	18	17.20	0.68	1.00	1.00	28.72	19.53	0.88
Lloyd &Wright (1990)	65	8B S8	S	0.75	3.94	65.000 *	2	18	21.13	0.68	1.00	1.00	28.72	19.53	1.08
Lloyd &Wright (1990)	65	8C S8	S	0.75	3.94	65.000 *	2	18	20.53	0.68	1.00	1.00	28.72	19.53	1.05
Lloyd &Wright (1990)	66	9A S9	S	0.75	3.94	65.000 *	2	18	19.27	0.68	1.00	1.00	28.72	19.53	0.99
Lloyd &Wright (1990)	66	9B S9	S	0.75	3.94	65.000 *	2	18	20.39	0.68	1.00	1.00	28.72	19.53	1.04
Lloyd &Wright (1990)	66	9C S9	S	0.75	3.94	65.000 *	2	18	19.94	0.68	1.00	1.00	28.72	19.53	1.02
Lloyd &Wright (1990)	67	10A S10	S	0.75	3.94	65.000 *	2	18	21.74	0.68	1.00	1.00	28.72	19.53	1.11
Lloyd &Wright (1990)	67	10B S10	S	0.75	3.94	65.000 *	2	18	21.92	0.68	1.00	1.00	28.72	19.53	1.12
Lloyd &Wright (1990)	67	10C S10	S	0.75	3.94	65.000 *	2	18	21.92	0.68	1.00	1.00	28.72	19.53	1.12
Lloyd &Wright (1990)	68	11A A1	S	0.75	3.94	65.000 *	2	18	25.47	0.68	1.00	1.00	28.72	19.53	1.30
Lloyd &Wright (1990)	68	11B A1	S	0.75	3.94	65.000 *	2	18	24.05	0.68	1.00	1.00	28.72	19.53	1.23
Lloyd &Wright (1990)	68	11C A1	S	0.75	3.94	65.000 *	2	18	25.58	0.68	1.00	1.00	28.72	19.53	1.31
Lloyd &Wright (1990)	69	12A A2	S	0.75	3.94	65.000 *	2	18	24.62	0.68	1.00	1.00	28.72	19.53	1.26
Lloyd &Wright (1990)	69	12B A2	S	0.75	3.94	65.000 *	2	18	23.54	0.68	1.00	1.00	28.72	19.53	1.21
Lloyd &Wright (1990)	69	12C A2	S	0.75	3.94	65.000 *	2	18	23.34	0.68	1.00	1.00	28.72	19.53	1.20

* Value for F_u not given. Assumed 65 ksi.

** Average of series reported.

Table 6.24 VT Strength Model Compared with Published Data (cont'd.)

Program	Series	Test	Stud Layout	Stud Diameter (in.)	Stud Height A.W. (in.)	Stud Fu (ksi)	Deck Height (in.)	Deck Gauge	Q_e (k)	R_p	R_n	R_d	A_sF_u (k)	Qsc (k)	Q_e/ Qsc
Lloyd &Wright (1990)	70	13A A3	S	0.75	3.94	65.000 *	2	18	22.03	0.68	1.00	1.00	28.72	19.53	1.13
Lloyd &Wright (1990)	70	13B A3	S	0.75	3.94	65.000 *	2	18	23.09	0.68	1.00	1.00	28.72	19.53	1.18
Lloyd &Wright (1990)	70	13C A3	S	0.75	3.94	65.000 *	2	18	21.54	0.68	1.00	1.00	28.72	19.53	1.10
Mottram & Johnson (1990)	H25-1	**	S	0.75	3.74	70.486	2	?	20.88	0.68	1.00	1.00	31.14	21.18	0.99
Mottram & Johnson (1990)	H30-1	**	S	0.75	3.74	70.486	2	?	22.68	0.68	1.00	1.00	31.14	21.18	1.07
Mottram & Johnson (1990)	H30L-1	**	S	0.75	3.74	70.486	2	?	21.67	0.68	1.00	1.00	31.14	21.18	1.02
Mottram & Johnson (1990)	H40-1	**	S	0.75	3.74	70.486	2	?	24.08	0.68	1.00	1.00	31.14	21.18	1.14
Mottram & Johnson (1990)	H30-2-50	**	2S	0.75	3.74	70.486	2	?	16.05	0.68	0.85	1.00	31.14	18.00	0.89
Mottram & Johnson (1990)	H30-2-76	**	2S	0.75	3.74	70.486	2	?	17.47	0.68	0.85	1.00	31.14	18.00	0.97
Mottram & Johnson (1990)	R30-1-U	**	W	0.75	3.74	70.486	2.36	?	17.54	0.48	1.00	1.00	31.14	14.95	1.17
Mottram & Johnson (1990)	R30-1-F	**	S	0.75	3.74	70.486	2.36	?	25.70	0.68	1.00	1.00	31.14	21.18	1.21
Mottram & Johnson (1990)	30-1-U	**	W	0.75	4.72	78.608	2.36	?	20.48	0.48	1.00	1.00	34.73	16.67	1.23
Mottram & Johnson (1990)	R30-2	**	2L (1S & 1W	0.75	3.74	70.486	2.36	?	16.96	0.58	0.85	1.00	31.14	15.35	1.10
Mottram & Johnson (1990)	R30-2-S	**	STAG	0.75	3.74	70.486	2.36	?	15.85	0.52	1.00	1.00	31.14	16.19	0.98
Mottram & Johnson (1990)	R30-2-S	**	STAG	0.75	3.74	70.486	2.36	?	17.87	0.52	1.00	1.00	31.14	16.19	1.10
Mottram & Johnson (1990)	P30-1-U	**	W	0.75	3.74	70.486	1.81	?	20.14	0.48	1.00	1.00	31.14	14.95	1.35
Robinson (1988)	QI	**	S	0.75	4.6	65.000 *	3	?	18.35	0.68	1.00	1.00	28.72	19.53	0.94
Robinson (1988)	QII	**	2S	0.75	4.6	65.000 *	3	?	12.03	0.68	0.85	1.00	28.72	16.60	0.72
Robinson (1988)	TI	**	S	0.75	4.6	65.000 *	3	?	23.72	0.68	1.00	1.00	28.72	19.53	1.21
Robinson (1988)	RI	**	W	0.75	3.6	65.000 *	2	?	18.66	0.48	1.00	1.00	28.72	13.78	1.35
Robinson (1988)	RII	**	2W	0.75	3.6	65.000 *	2	?	16.78	0.48	0.85	1.00	28.72	11.72	1.43
Robinson (1988)	TVII	**	W	0.75	4.6	65.000 *	3	?	21.85	0.48	1.00	1.00	28.72	13.78	1.59
Robinson (1988)	TII	**	2S	0.75	4.6	65.000 *	3	?	14.52	0.68	0.85	1.00	28.72	16.60	0.88
Robinson (1988)	TVIII	**	2W	0.75	4.6	65.000 *	3	?	10.74	0.48	0.85	1.00	28.72	11.72	0.92
Johnson and Yuan (1997)	G1F	G1F-1	S	0.75	4.92	68.458	3.15	18	20.93	0.68	1.00	1.00	30.24	20.57	1.02
Johnson and Yuan (1997)	G1F	G1F-2	S	0.75	4.92	68.458	3.15	18	20.37	0.68	1.00	1.00	30.24	20.57	0.99
Johnson and Yuan (1997)	G2C	G2C-1	S	0.75	4.92	68.458	2.17	20	19.96	0.68	1.00	1.00	30.24	20.57	0.97
Johnson and Yuan (1997)	G2C	G2C-2	S	0.75	4.92	68.458	2.17	20	19.78	0.68	1.00	1.00	30.24	20.57	0.96
Johnson and Yuan (1997)	G3FL	G3FL-1	S	0.75	4.92	68.458	3.15	18	19.40	0.68	1.00	1.00	30.24	20.57	0.94
Johnson and Yuan (1997)	G3FL	G3FL-2	S	0.75	4.92	68.458	3.15	18	19.56	0.68	1.00	1.00	30.24	20.57	0.95
Johnson and Yuan (1997)	G4FL	G4FL-1	S	0.75	3.74	70.488	2.36	20	14.55	0.68	1.00	1.00	31.14	21.18	0.69
Johnson and Yuan (1997)	G4FL	G4FL-2	S	0.75	3.74	70.488	2.36	20	15.49	0.68	1.00	1.00	31.14	21.18	0.73
Johnson and Yuan (1997)	G5U	G5U-1	W	0.75	4.92	68.458	3.15	18	15.94	0.48	1.00	1.05	30.24	15.24	1.05
Johnson and Yuan (1997)	G5U	G5U-2	W	0.75	4.92	68.458	3.15	18	15.17	0.48	1.00	1.05	30.24	15.24	1.00
Johnson and Yuan (1997)	G6U	G6U-1	W	0.75	3.74	70.488	2.36	20	11.53	0.48	1.00	1.00	31.14	14.95	0.77
Johnson and Yuan (1997)	G6U	G6U-2	W	0.75	3.74	70.488	2.36	20	12.09	0.48	1.00	1.00	31.14	14.95	0.81
Johnson and Yuan (1997)	G7D	G7D-1	2L (1W & 1S	0.75	3.74	70.488	2.36	20	11.20	0.58	0.85	1.00	31.14	15.35	0.73
Johnson and Yuan (1997)	G7D	G7D-2	2L (1W & 1S	0.75	3.74	70.488	2.36	20	11.60	0.58	0.85	1.00	31.14	15.35	0.76
Johnson and Yuan (1997)	G8D	G8D-1	2L (1W & 1S	0.75	4.92	68.458	3.15	18	13.80	0.58	0.85	1.05	30.24	15.66	0.88
Johnson and Yuan (1997)	G8D	G8D-2	2L (1W & 1S	0.75	4.92	68.458	3.15	18	13.51	0.58	0.85	1.05	30.24	15.66	0.86

* Value for F_u not given. Assumed 65 ksi.

** Average of series reported.

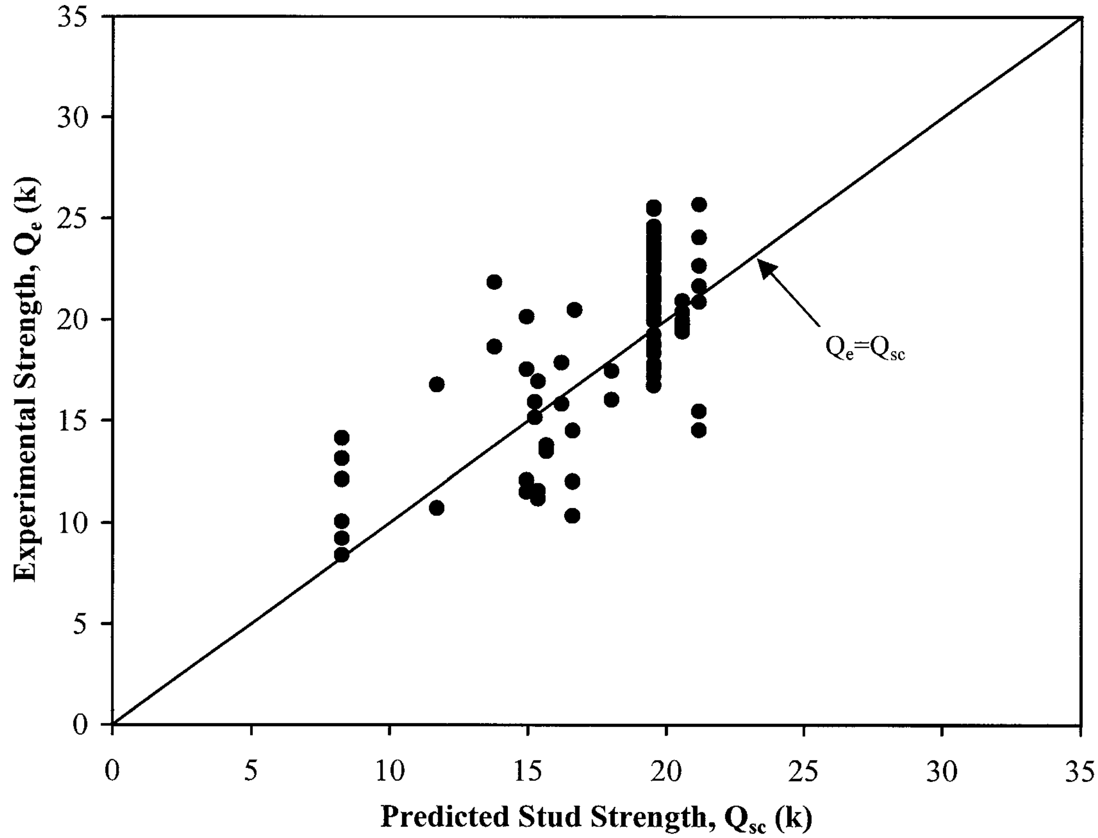

Fig. 6.18 Experimental Stud Strength vs. Predicted Stud Strength for Other Tests Using New Model